

# **Digital Elevation Models of the San Juan Islands, Washington: Procedures, Data Sources and Analysis**

Prepared for the National Tsunami Hazard Mitigation Program (NTHMP)

Research by the NOAA National Geophysical Data Center (NGDC)

December 23, 2011

Lim, E.<sup>1</sup>, L.A. Taylor<sup>2</sup>, B.W. Eakins<sup>1</sup>, K.S. Carignan<sup>1</sup>, M.R. Love<sup>1</sup>, P.R. Grothe<sup>1</sup>, D.Z. Friday<sup>1</sup>

<sup>1</sup>Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder

<sup>2</sup>NOAA, National Geophysical Data Center, Boulder, Colorado

*Corresponding project contact:*

Lisa A. Taylor

NOAA, National Geophysical Data Center

Marine Geology and Geophysics Division

325 Broadway, E/GC 3

Boulder, Colorado 80305

Phone: 303-497-6767

Fax: 303-497-6513

E-mail: [Lisa.A.Taylor@noaa.gov](mailto:Lisa.A.Taylor@noaa.gov)

<http://www.ngdc.gov/mgg/coastal/>



## CONTENTS

1. Introduction.....	1
2. Study Area.....	2
3. Methodology.....	3
3.1 Data Sources and Processing.....	4
3.1.1 Shoreline.....	5
3.1.2 Bathymetry.....	7
3.1.3 Topography.....	14
3.2 Establishing Common Datums.....	18
3.2.1 Vertical datum transformations.....	18
3.2.2 Horizontal datum transformations.....	18
3.3 Digital Elevation Model Development.....	19
3.3.1 Verifying consistency between datasets.....	19
3.3.2 Processing of bathymetric data.....	19
3.3.3 Building the NAVD 88 DEM.....	21
3.3.4 Building the MHW DEM.....	21
3.4 Quality Assessment of the DEM.....	24
3.4.1 Horizontal accuracy.....	24
3.4.2 Vertical accuracy.....	24
3.4.3 Slope map and 3-D perspectives.....	24
3.4.4 Comparison with National Geodetic Survey geodetic monuments.....	28
3.4.5 NAVD 88 DEM comparison with source data files.....	29
4. Summary and Conclusions.....	31
5. Acknowledgments.....	31
6. References.....	31
7. Data Processing Software.....	31

## LIST OF FIGURES

Figure 1. Shaded-relief image of the San Juan Islands NAVD 88 1/3 arc-second DEM.....	1
Figure 2. Photograph of the coastal zone in Friday Harbor, WA.....	2
Figure 3. Source and coverage of datasets used in compiling the San Juan Islands NAVD 88 DEM.....	4
Figure 4. Digital shoreline datasets used in developing a combined shoreline of the San Juan Islands region.....	5
Figure 5. Combined shoreline of San Juan Islands Harbor shown with ESRI World 2D Imagery.....	6
Figure 6. Source and coverage of bathymetric datasets used in compiling the San Juan Islands DEMs.....	7
Figure 7. Digital NOS hydrographic survey coverage in the San Juan Islands region.....	8
Figure 8. Examples of gross anomalies in the CHS bathymetric data.....	11
Figure 9. Color shaded-relief image of the coverage of the MLML bathymetric data.....	12
Figure 10. NGDC digitized points referenced to RNC #18440.....	13
Figure 11. Source and coverage of topographic datasets used in the San Juan Islands DEMs.....	14
Figure 12. Coverage of the NED 1/3 arc-second topographic DEM.....	15
Figure 13. Data gaps and anomalies in the NED 1/9 arc-second DEM.....	16
Figure 14. Color shaded-relief image of the CDED topographic DEM.....	17
Figure 15. Histogram of the differences between NOS hydrographic survey H11316 and the 1/3 arc-second pre-surfaced bathymetric grid.....	20
Figure 16. Histogram of the differences between NED 1/9 data and the 1/3 arc-second pre-surfaced bathymetric grid.....	20
Figure 17. Image of the NAVD88 to MHW conversion grid.....	22
Figure 18. Histogram of the differences between the conversion grid and NOS hydrographic data.....	23
Figure 19. Slope map of the San Juan Islands NAVD88 DEM.....	25
Figure 20. Color-shaded relief image of the NAVD88 San Juan Islands DEM.....	26

Figure 21.	Data contribution plot of the NAVD88 San Juan Islands DEMs .....	27
Figure 22.	Location of NGS geodetic monuments in the San Juan Islands region .....	28
Figure 23.	Histogram of the differences between NGS Geodetic Elevations and the San Juan Islands NAVD 88 DEM.....	29
Figure 24.	Histogram of the differences between select PSLC data points and the San Juan Islands NAVD 88 DEM.....	30
Figure 25.	Histogram of the differences between select NED 1/9 data points and the San Juan Islands NAVD 88 DEM.....	30
Figure 36.	Histogram of the differences between CDED topographic data points and the San Juan Islands NAVD 88 DEM .....	30

## LIST OF TABLES

Table 1.	Specifications for the San Juan Islands DEMs .....	3
Table 2.	Shoreline datasets used in developing the San Juan Islands DEMs .....	5
Table 3.	Bathymetric datasets used in compiling the San Juan Islands DEMs .....	7
Table 4.	Digital NOS hydrographic surveys in the San Juan Islands region .....	9
Table 5.	Topographic datasets used in compiling the San Juan Islands DEMs. ....	14
Table 6.	Relationship between NAVD 88 and other vertical datums at the Port Angeles tide station ..	18
Table 7.	Data hierarchy used to assign gridding weight in MB-System.....	21

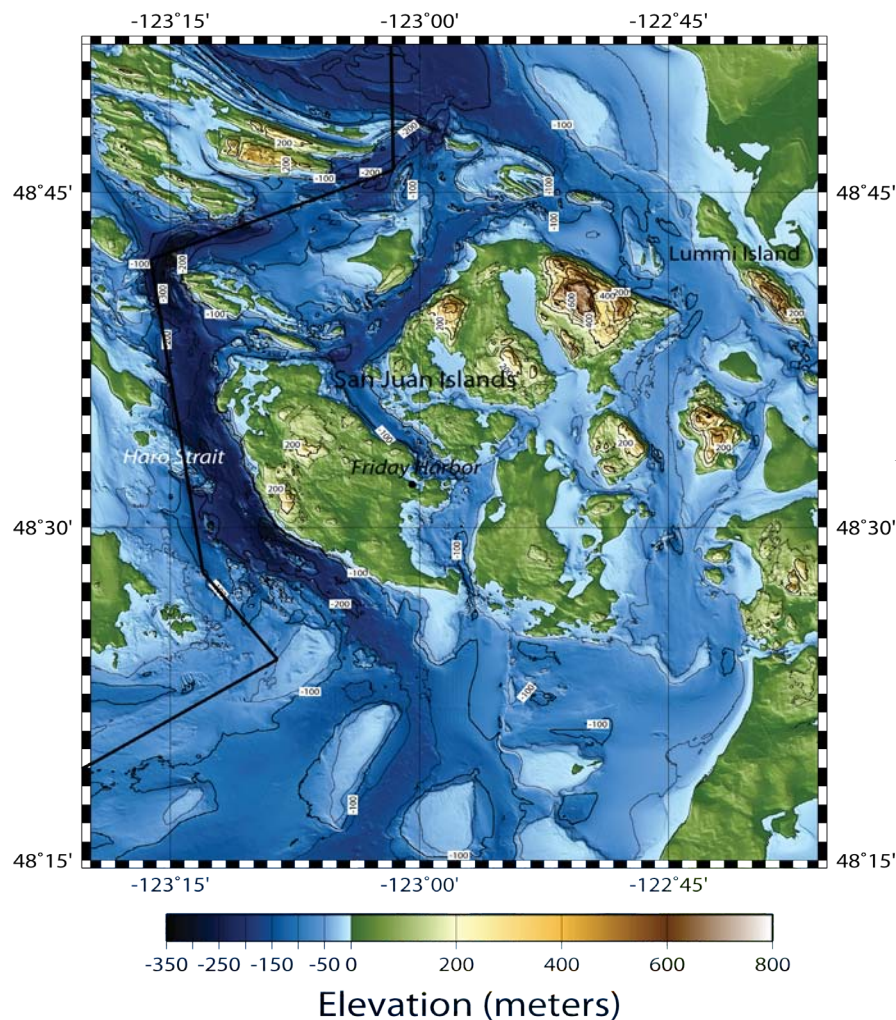
# Digital Elevation Models of San Juan Islands, Washington: Procedures, Data Sources and Analysis

## 1. INTRODUCTION

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two 1/3<sup>1</sup> arc-second bathymetric–topographic digital elevation models (DEMs) centered on the San Juan Islands in the state of Washington (Fig. 1).

A 1/3 arc-second DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was carefully developed and evaluated. An NAVD 88 to mean high water (MHW) 1/3 arc-second conversion grid was then created to represent the relationship between NAVD 88 and MHW in the San Juan Islands region. A 1/3 arc-second MHW DEM, created by combining the NAVD 88 DEM and the conversion grid will be used by the National Tsunami Hazard Mitigation Program (NTHMP; <http://nthmp.tsunami.gov/>) in support of the State of Washington’s tsunami inundation modeling and hazard mitigation efforts led by the University of Washington. This report provides a summary of the data sources and methodology used in developing the San Juan Islands DEMs.

### Bathymetry and Topography of the San Juan Islands, WA



*Figure 1. Shaded-relief image of the San Juan Islands NAVD88 1/3 arc-second DEM. Contour interval is 100 meters for topography and 50 meters for bathymetry. Bold black line represents the USA-CA border. Image is in Mercator projection.*

1. The San Juan Island DEMs were built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Friday Harbor, WA, (48° 32' 7" N, 123° 1' 52" W) 1/3 arc-second of latitude is equivalent to 10.4938 meters; 1/3 arc-second of longitude equals 6.7313 meters.

## 2. STUDY AREA

The San Juan Islands, WA DEMs span across a diverse variety of landscapes, which include mud-flats, rocky shores, mountains, tidal-flats, and floodplains. This region is composed of a series of underwater basins and sills, which are the result of the Cascadia subduction zone and the Wisconsin Glaciation ([http://www.tititodorancea.com/z/puget\\_sound.htm](http://www.tititodorancea.com/z/puget_sound.htm)).

The last major subduction zone earthquake in this region was a magnitude 8.7 that occurred in the Cascadia subduction zone in 1700. The length of the fault rupture was approximately 1000 kilometers with an average slip of 20 meters. The geological record reveals that earthquakes with a moment magnitude of 8 or higher occur every 500 years on average and are often accompanied by tsunamis. Previous earthquakes are estimated to have occurred in 1310 AD, 810 AD, 400 AD, 170 BC, and 600 BC (<http://www.cosmosmagazine.com/node/3437/full>).



Figure 2. Landscape and coastal zone of Friday Harbor, WA.

Source: [http://en.wikipedia.org/wiki/File:Aerial\\_Friday\\_Harbor\\_Washington\\_August\\_2009.jpg](http://en.wikipedia.org/wiki/File:Aerial_Friday_Harbor_Washington_August_2009.jpg)

### 3. METHODOLOGY

The San Juan Islands DEMs were constructed to meet NTHMP specifications (Table 1). The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983<sup>2</sup> HARN Washington State Plane South and NAVD 88, respectively. *MB-System* was used to convert the NAD83 geographic San Juan Islands DEMs into a NAD83 HARN Washington State Plane South horizontal datum. The resulting NAVD 88 DEM was then transformed to MHW using a conversion grid for modeling of maximum flooding (see section 3.3.4). Data were gathered in an area slightly larger (~5%) than the DEM extents. This data “buffer” ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing, evaluation, DEM assembly and assessment are described in the following subsections.

**Table 1. NTHMP specifications for the San Juan Islands, WA DEMs.**

<b>Grid Area</b>	San Juan Islands, Washington
<b>Coverage Area</b>	123.33° to 122.60° W; 48.25° to 48.86° N
<b>Coordinate System</b>	State Plane Feet
<b>Horizontal Datum</b>	NAD 83 HARN Washington State Plane South (ft)
<b>Vertical Datums</b>	A. North American Vertical Datum of 1988 (NAVD 88) B. Mean High Water
<b>Vertical Units</b>	Meters
<b>Cell Size</b>	1/3 arc-second
<b>Grid Format</b>	ESRI Arc ASCII raster grid

---

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEMs. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEM so that they can model the wave’s passage across ocean basins. The DEMs are identified as having a NAD 83 HARN Washington State Plane South horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic.

### 3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state, and international agencies including: NGDC; NOAA's National Ocean Service (NOS), Coastal Services Center (CSC), and Office of Coast Survey (OCS); the Canadian Hydrographic Service (CHS), the Canadian Digital Elevation Data (CDED); Washington State Department of Ecology (WSDE); Puget Sound Lidar Consortium (PSLC); Moss Landing Marine Laboratory (MLML); and the U.S. Geological Survey (USGS). Datasets were shifted to NAD 83 geographic horizontal datum and converted into ESRI shapefiles and ASCII xyz files. ESRI shapefiles were then displayed with *ArcGIS* and the xyz files were displayed with Applied Imagery's *Quick Terrain Modeler (QT Modeler)* to assess data quality and manually edit datasets. *MB-System* was then used to convert the San Juan Islands DEMs from a horizontal datum of NAD 83 geographic to NAD 83 HARN Washington State Plane South. Vertical datum transformations to NAVD 88 were accomplished using NOAA's *Vertical Datum (VDatum)* transformation tool. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

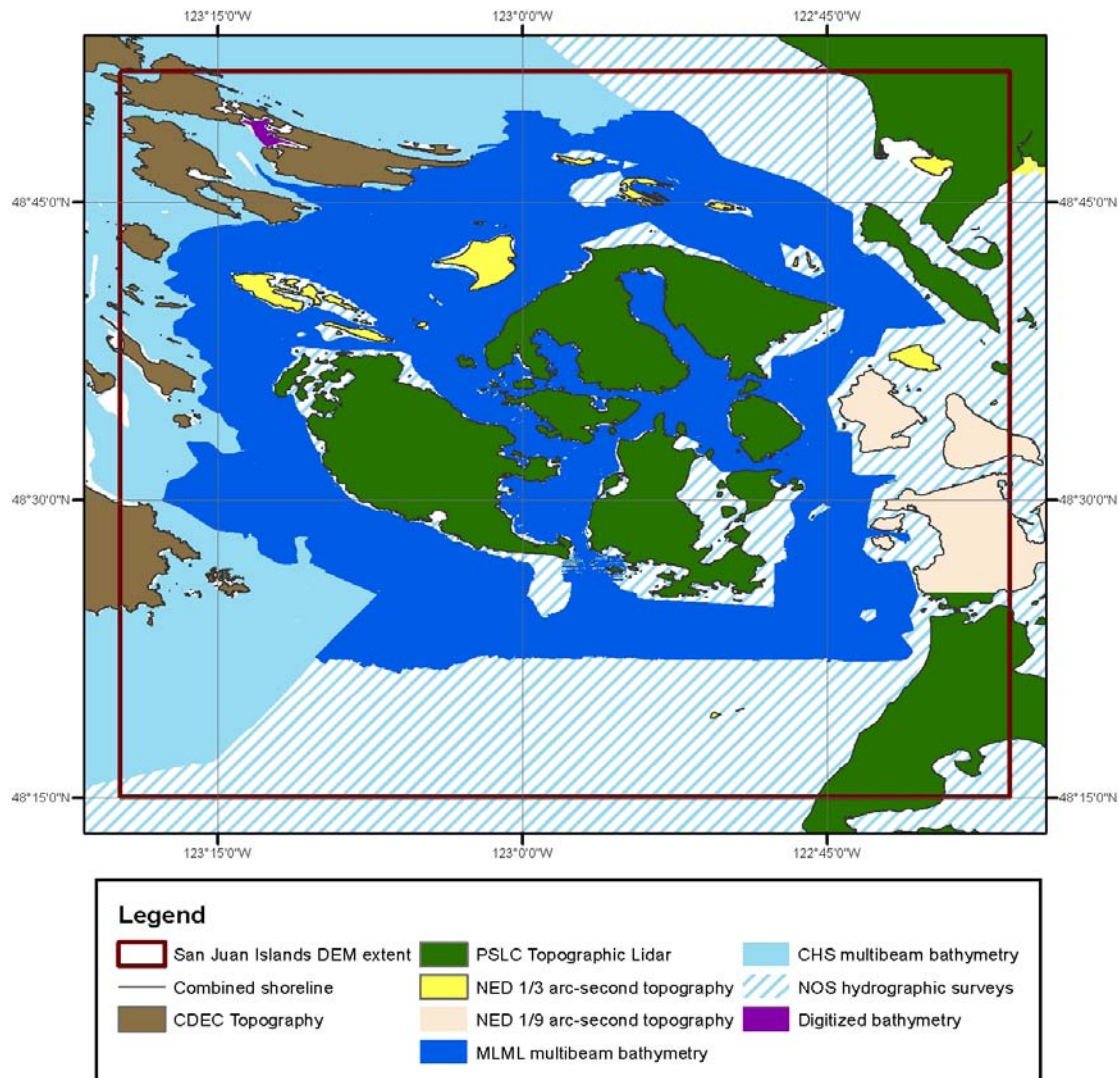


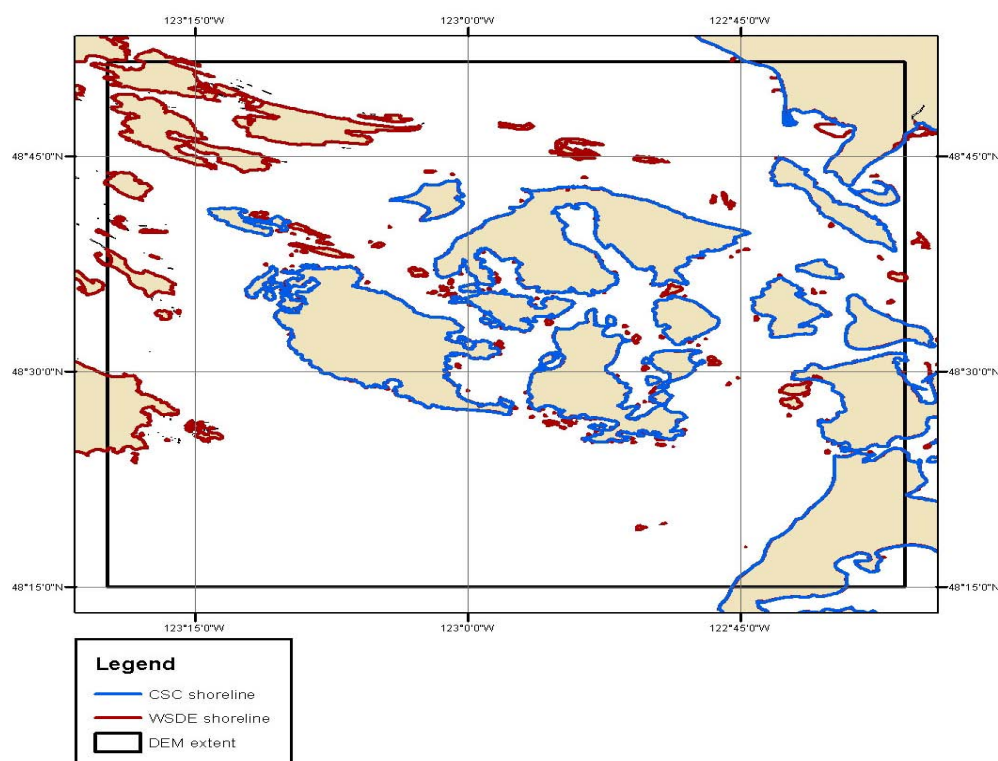
Figure 3. Source and coverage of datasets used in compiling the San Juan Islands DEMs.

### 3.1.1 Shoreline

Shoreline datasets of the San Juan Islands region were obtained from WSDE, CSC, and OCS (Table 2; Fig. 4). Shorelines from NOAA's OCS were obtained as Electronic Navigational Charts (ENCs)<sup>3</sup> and were evaluated but were not used because of inconsistencies in coverage and lower spatial resolutions. The two remaining datasets were edited and merged to develop a "combined shoreline" of the San Juan Islands region.

**Table 2.** Shoreline datasets used in developing the San Juan Islands DEMs.

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/ Coordinate System	Original Vertical Datum	URL
WSDE	2001	vector shoreline	1:24,000	NAD 83 HARN State Plane WA South	Mean high water	<a href="http://www.ecy.wa.gov/services/gis/data/data.htm">http://www.ecy.wa.gov/services/gis/data/data.htm</a>
CSC	1995	vector shoreline	1:24,000	NAD 83 geographic	Mean sea level	<a href="http://www.csc.noaa.gov/">http://www.csc.noaa.gov/</a>



*Figure 4.* Digital shoreline datasets used in developing a combined shoreline of the San Juan Islands region. Water areas shown in white. Land areas shown in beige.

3. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: <http://nauticalcharts.noaa.gov/mcd/enc/>]

### 1) Washington State Department of Ecology (WSDE)

The WSDE shoreline dataset includes Puget Sound, Hood Canal, the Strait of Juan de Fuca, and the Pacific coastline. In support of the Southwest Washington Coastal Erosion Study, WSDE edited, digitized, and updated the shoreline using USGS 7.5' quadrangles to define the mean high tide line between 2000-2010. It was made available to NGDC in an *ESRI* shapefile format.

### 2) NOAA's Coastal Services Center

NOAA's CSC compiled a vector shoreline using multi-temporal collection of NOAA coastal survey maps (T-sheets) ranging from 1901-1995. Where T-sheets were unavailable, NOAA's Extracted Vector Shoreline (EVS) was used to compile seamless shoreline coverage throughout the region.

The WSDE and CSC shoreline datasets were merged using *ArcCatalog* and used to create a "combined shoreline" of the San Juan Islands region. The combined shoreline was modified to include large offshore rocks, breakwaters, harbors, and small inlets as shown on the larger-scale RNCs, USGS quadrangles and ESRI's *World 2D* imagery (e.g., Fig 5). ESRI's *World 2D* imagery was used to identify piers and docks, which were removed from the combined shoreline, and to reflect the most current coastal morphology. The combined shoreline was clipped to 0.05 degrees larger than the DEM boundary to allow for interpolation along the edges of the DEMs.



Figure 5. Combined shoreline (green line) shown with ESRI World 2D Imagery. Piers are not included in the shoreline as water can flow beneath them, but large rocks and breakwaters were included as they are solid structures.

### 3.1.2 Bathymetry

Bathymetric datasets available for use in the compilation of the San Juan Islands DEMs include 133 NOS hydrographic surveys; CHS multibeam bathymetry, MLML multibeam bathymetry, and NGDC digitized bathymetry. (Table 3; Fig. 6).

Table 3. Bathymetric datasets used in compiling the San Juan Islands DEMs.

<i>Source</i>	<i>Year</i>	<i>Data Type</i>	<i>Spatial Resolution</i>	<i>Original Horizontal Datum/Coordinate System</i>	<i>Original Vertical Datum</i>	<i>URL</i>
NGDC	1887 to 2006	NOS hydrographic survey soundings	Ranges from 5 meters to 1.2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 83 geographic, NAD 83 UTM Zone 10 North	MLW and MLLW	<a href="http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html">http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html</a>
CHS	2010	Gridded data	1 arc-second	WGS 84 geographic	Assumed MSL	<a href="http://www.dfo-mpo.gc.ca/index-eng.htm">http://www.dfo-mpo.gc.ca/index-eng.htm</a>
MLML	2001	Gridded data	~10 meters	WGS 84 UTM 10N	Assumed MSL	<a href="http://www.mlml.calstate.edu/">http://www.mlml.calstate.edu/</a>
NGDC	2010	digitized points	n/a	WGS 84 geographic	NAVD 88	n/a

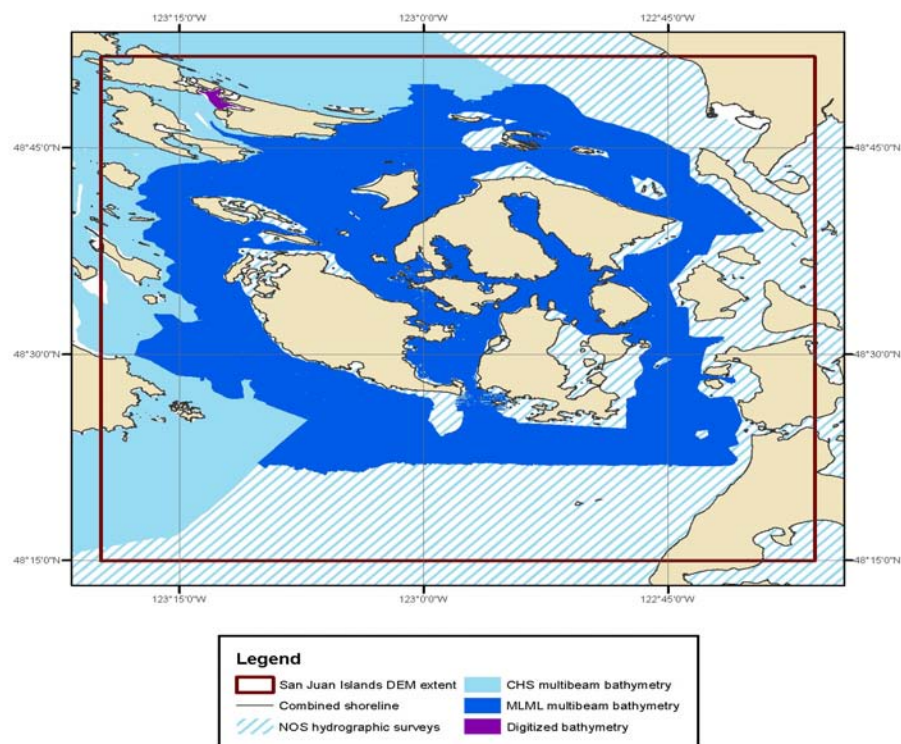


Figure 6. Source and coverage of bathymetric datasets used in compiling the San Juan Islands DEM.

### 1) National Ocean Service hydrographic survey data

A total of 76 NOS hydrographic surveys conducted between 1887 and 2004 were available for use in developing the San Juan Islands DEMs. Surveys were extracted as xyz files using *GEODAS*<sup>4</sup> from NGDC's online NOS hydrographic database with a buffer 0.05 degrees (~5%) larger than the San Juan Islands DEM area to support data interpolation along grid edges. The downloaded digital hydrographic survey data were vertically referenced to mean low water (MLW) or mean lower low water (MLLW) and horizontally referenced to NAD 83 geographic and NAD 83 UTM Zone 10 North (Table 4; Fig. 7).

Data point spacing for the NOS surveys varied by scale. In general, small scale surveys had greater point spacing than large scale surveys. All NOS survey data were converted to NAVD 88 using the *VDatum* transformation tool (see Sec. 3.2.1). The data were then converted to shapefiles using *FME* software and displayed in ESRI *ArcMap* and reviewed for digitizing errors and edited as necessary. The surveys were also compared to other bathymetric datasets, the combined shoreline, NOAA RNCs, and USGS 7.5' quadrangles. Older surveys were clipped to remove soundings that have been superseded by more recent NOS surveys and bathymetric multibeam data.

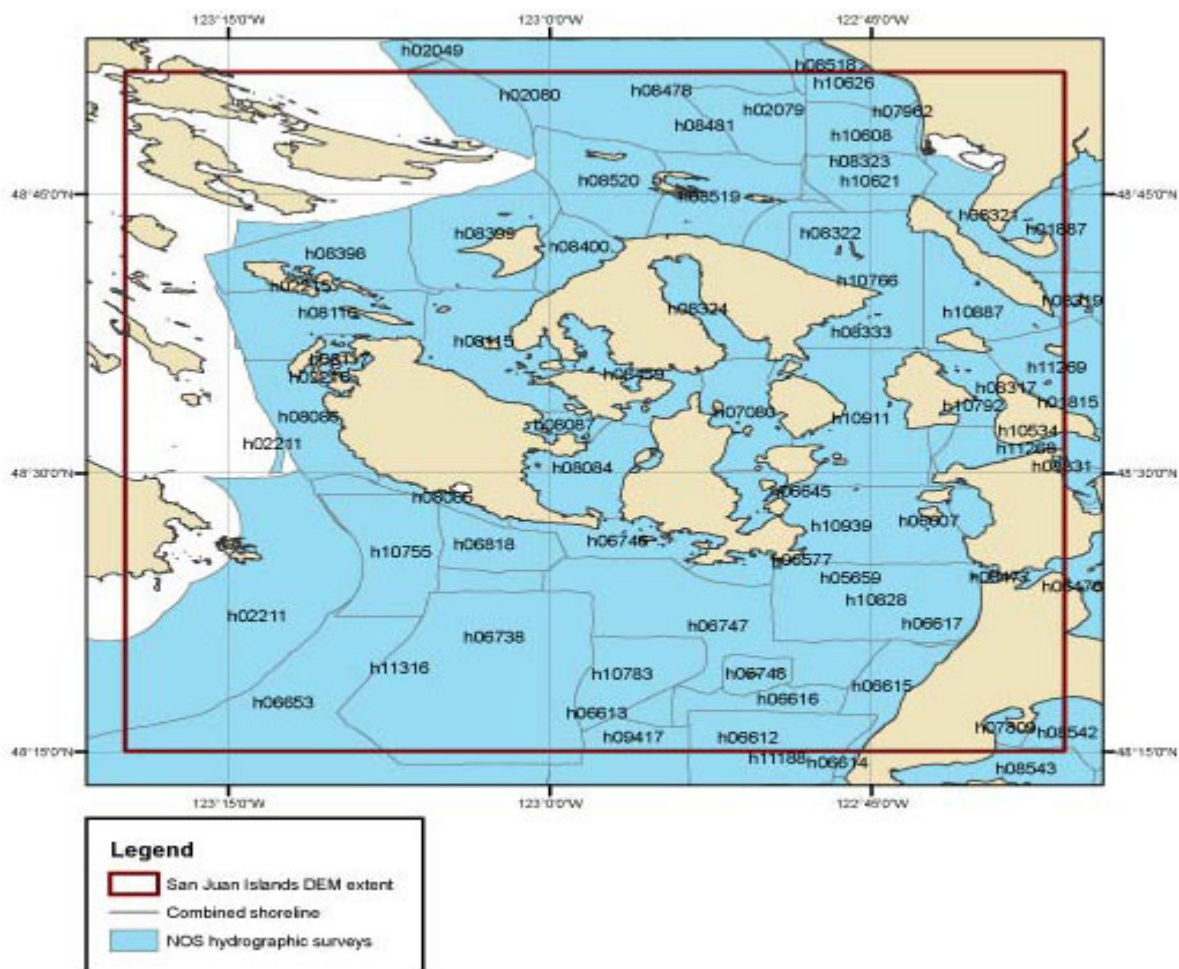


Figure 7. Digital NOS hydrographic survey coverage in the San Juan Islands region.

4. *GEODAS* uses the North American Datum Conversion Utility (NADCON; <http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml>) developed by NOAA's National Geodetic Survey (NGS) to convert hydrographic survey data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

**Table 4. Digital NOS hydrographic surveys in the San Juan Islands region.**

<i>NOS Survey ID</i>	<i>Year of Survey</i>	<i>Survey Scale</i>	<i>Original Horizontal Datum</i>	<i>Original Vertical Datum</i>
F00399	1994	5,000	Mean Lower Low Water	North American Datum of 1983
H01815 <sup>+</sup>	1887	20,000	Mean Low Water	North American Datum of 1983
H02049	1890	20,000	Mean Low Water	North American Datum of 1983
H02079	1889	20,000	Mean Low Water	North American Datum of 1983
H02080	1891	20,000	Mean Low Water	North American Datum of 1983
H02211	1894	40,000	Mean Lower Low Water	North American Datum of 1983
H02215	1894	10,000	Mean Lower Low Water	North American Datum of 1983
H02216	1894	10,000	Mean Lower Low Water	North American Datum of 1983
H05659	1935	20,000	Mean Lower Low Water	North American Datum of 1983
H06476	1939	10,000	Mean Lower Low Water	North American Datum of 1983
H06477	1939	5,000	Mean Lower Low Water	North American Datum of 1983
H06577	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06607	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06612	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06613	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06614	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06615	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06616	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06617	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06645	1940	10,000	Mean Lower Low Water	North American Datum of 1983
H06653	1943	40,000	Mean Lower Low Water	North American Datum of 1983
H06738	1942	20,000	Mean Lower Low Water	North American Datum of 1983
H06746	1943	10,000	Mean Lower Low Water	North American Datum of 1983
H06747	1941	20,000	Mean Lower Low Water	North American Datum of 1983
H06748	1941	10,000	Mean Lower Low Water	North American Datum of 1983
H06818	1943	20,000	Mean Lower Low Water	North American Datum of 1983
H07045	1945	20,000	Mean Lower Low Water	North American Datum of 1983
H07080	1947	10,000	Mean Lower Low Water	North American Datum of 1983
H07809	1951	10,000	Mean Lower Low Water	North American Datum of 1983
H07962	1953	10,000	Mean Lower Low Water	North American Datum of 1983
H08084	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08085	1953	10,000	Mean Lower Low Water	North American Datum of 1983
H08086	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08087	1953	5,000	Mean Lower Low Water	North American Datum of 1983
H08115	1954	10,000	Mean Lower Low Water	North American Datum of 1983
H08116	1954	10,000	Mean Lower Low Water	North American Datum of 1983
H08117	1957	5,000	Mean Lower Low Water	North American Datum of 1983
H08317	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08319	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08320	1956	10,000	Mean Lower Low Water	North American Datum of 1983

<i>NOS Survey ID</i>	<i>Year of Survey</i>	<i>Survey Scale</i>	<i>Original Horizontal Datum</i>	<i>Original Vertical Datum</i>
H08321	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08322	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08323	1956	10,000	Mean Lower Low Water	North American Datum of 1983
H08324	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08331	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08331I	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08333	1955	10,000	Mean Lower Low Water	North American Datum of 1983
H08398	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08399	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08400	1957	10,000	Mean Lower Low Water	North American Datum of 1983
H08459	1958	10,000	Mean Lower Low Water	North American Datum of 1983
H08478	1959	30,000	Mean Lower Low Water	North American Datum of 1983
H08481	1959	10,000	Mean Lower Low Water	North American Datum of 1983
H08518	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08519	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08520	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H08542	1962	10,000	Mean Lower Low Water	North American Datum of 1983
H08543	1960	10,000	Mean Lower Low Water	North American Datum of 1983
H09417	1974	40,000	Mean Lower Low Water	North American Datum of 1983
H10534	1994	10,000	Mean Lower Low Water	North American Datum of 1983
H10535	1994	10,000	Mean Lower Low Water	North American Datum of 1983
H10608	1995	10,000	Mean Lower Low Water	North American Datum of 1983
H10621	1996	10,000	Mean Lower Low Water	North American Datum of 1983
H10626	1995	10,000	Mean Lower Low Water	North American Datum of 1983
H10755	1997	10,000	Mean Lower Low Water	North American Datum of 1983
H10766	1998	10,000	Mean Lower Low Water	North American Datum of 1983
H10783	1998	10,000	Mean Lower Low Water	North American Datum of 1983
H10792	2000	10,000	Mean Lower Low Water	North American Datum of 1983
H10828	1999	n/a	Mean Lower Low Water	North American Datum of 1983
H10887	1999	10,000	Mean Lower Low Water	North American Datum of 1983
H10911	1999	10,000	Mean Lower Low Water	North American Datum of 1983
H10939	1999	20,000	Mean Lower Low Water	North American Datum of 1983
H11188	2002	10,000	Mean Lower Low Water	North American Datum of 1983
H11268	2003	10,000	Mean Lower Low Water	North American Datum of 1983
H11269	2004	10,000	Mean Lower Low Water	North American Datum of 1983
H11316	2004	20,000	Mean Lower Low Water	North American Datum of 1983

+ Denotes excluded survey

## 2) Canadian Hydrographic Service multibeam bathymetry

Canadian multibeam bathymetry was provided by Rob Hare of CHS. A Memorandum Of Understanding (MOU)<sup>5</sup> was signed by NOAA and CHS giving NOAA permission to integrate CHS bathymetry into the San Juan Islands DEM in support of improved tsunami forecasting and warning. Surveys are in WGS 84 geographic, which NGDC gridded at a cell size of 1 arc-second and are in an assumed MSL vertical datum. Data anomalies were manually removed in *Fledermaus* (e.g., Fig. 8).

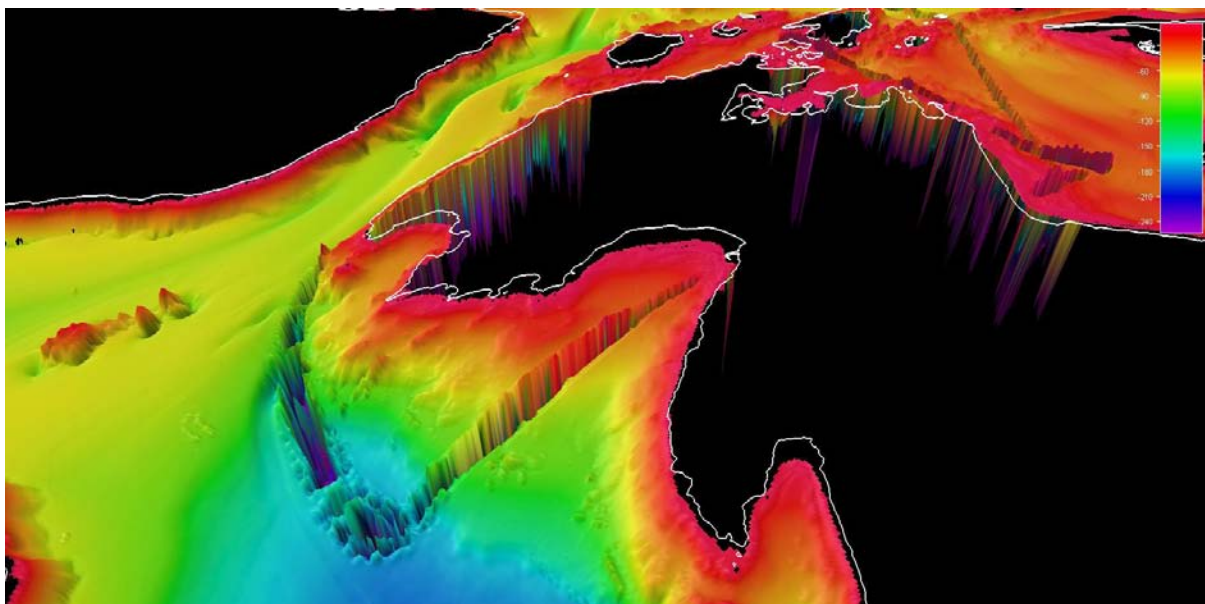


Figure 8. Examples of gross anomalies in the CHS multibeam bathymetry. Spikes were manually removed using *Fledermaus*.

---

5. The San Juan Islands DEMs have been produced by the National Oceanic Atmospheric Administration and includes Canadian Hydrographic Service Charts and/or Data, pursuant to CHS Memorandum of Understanding No. 2010-0611-1260-N. The incorporation of data sourced from CHS in this model shall not be construed as constituting an endorsement by CHS of this model. This model does not meet the requirements of the Charts and Nautical Publications Regulations under the *Canada Shipping Act, 2001*. Official charts and publications, corrected and up-to-date, must be used to meet the requirements of those regulations.

### 3) Moss Landing Marine Laboratory multibeam bathymetry

MLML provided proprietary<sup>6</sup> multibeam bathymetry for the San Juan Islands region. Bathymetric grids were provided with a cell spacing of ~10 meters, a horizontal datum of WGS 1984 UTM 10N, and a vertical datum assumed to be MSL.

MLML multibeam bathymetry were evaluated and edited in *Fledermaus*. In areas where NOS hydrographic, CHS multibeam bathymetry, and NGDC bathymetry overlapped MLML multibeam bathymetry, those data were clipped to take precedence on the MLML multibeam bathymetry (Fig. 9).

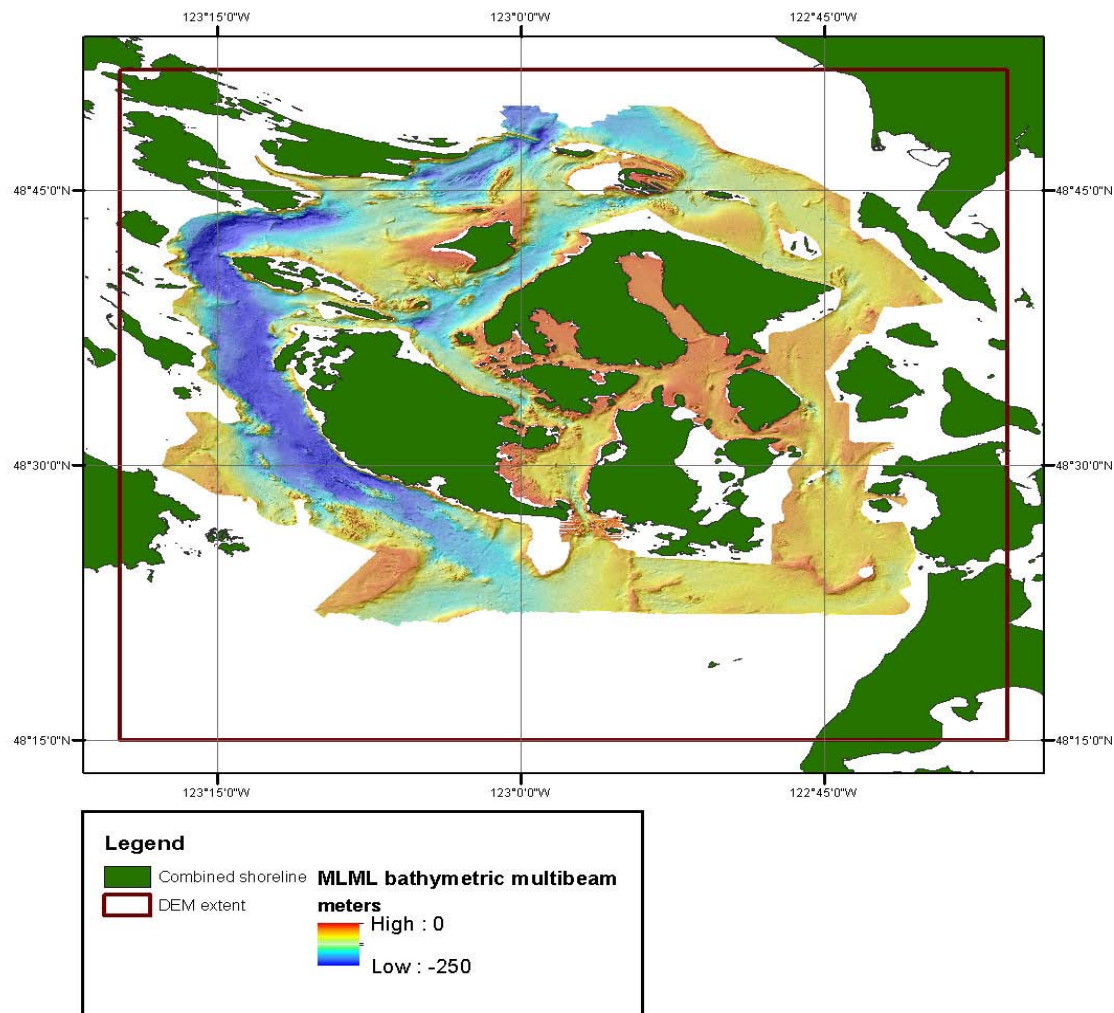


Figure 9. Color shaded-relief image displaying the coverage of the MLML bathymetric data.

6. The San Juan Islands DEM has been produced by the National Oceanic Atmospheric Administration and includes Moss Landing Marine Laboratory multibeam bathymetry. The incorporation of data sourced from MLML in this model shall not be construed as constituting an endorsement by MLML of this model. MLML source data is not available to the public.

#### 4) NGDC-digitized depths

NGDC digitized bathymetric values from Raster Nautical Charts (RNCs) obtained from NOAA's Office of Coast Survey in areas where digital bathymetric data were sparse or inconsistent with corresponding RNCs and satellite imagery. Figure 10 illustrates how depths were digitized to represent the seabed of Plumper Sound. Depth values were assigned to points based on RNC #18440.

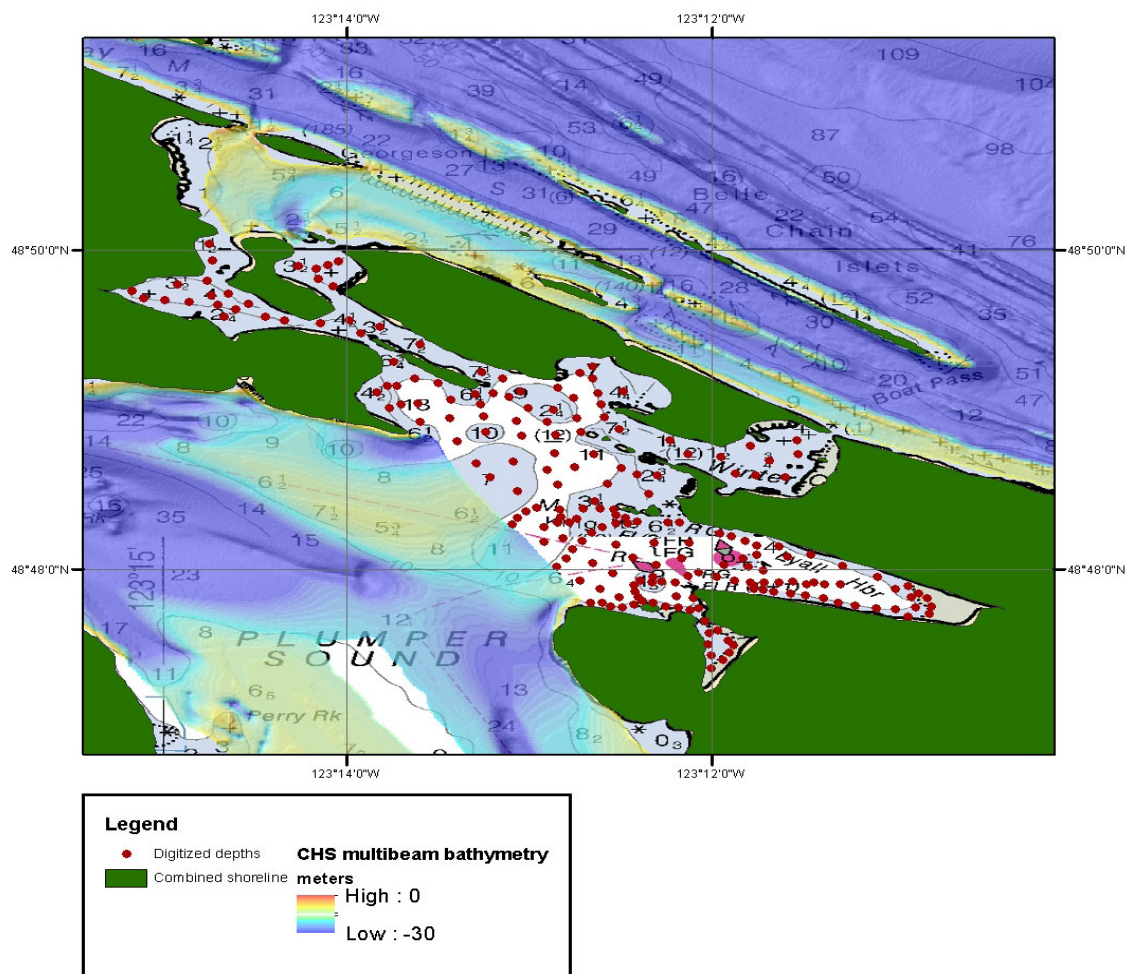


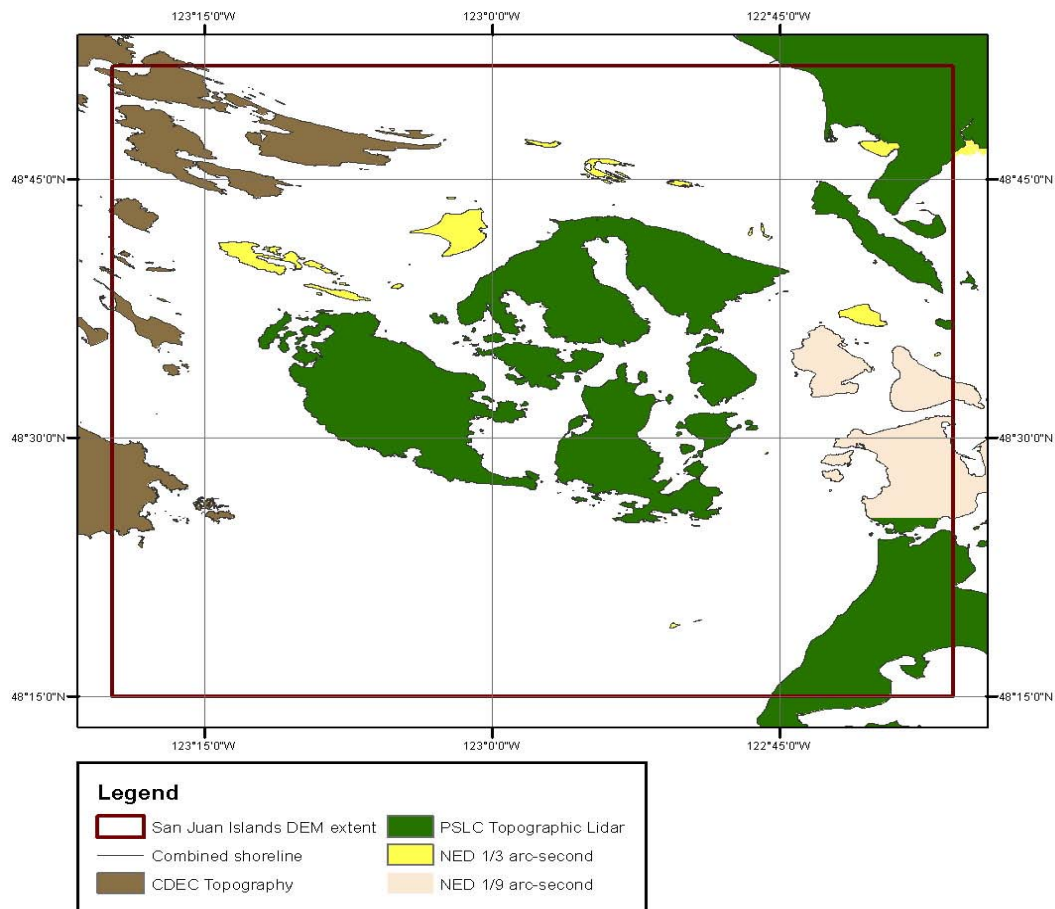
Figure 10. NGDC digitized points referenced to RNC #18440 in areas of sparse or no data.

### 3.1.3 Topography

The topographic datasets used to build the San Juan Islands DEMs include: USGS NED 1/3 and 1/9 arc-second DEMs, PSLC, and CDED (Table 5; Fig. 11).

**Table 5.** Topographic datasets used in compiling the San Juan Islands DEMs.

<i>Source</i>	<i>Year</i>	<i>Data Type</i>	<i>Spatial Resolution</i>	<i>Original Horizontal Datum/ Coordinate System</i>	<i>Original Vertical Datum</i>	<i>URL</i>
USGS NED	1999-2007	DEMs	1/3 and 1/9 arc-seconds	NAD 83 geographic	NAVD 88	<a href="http://ned.usgs.gov">http://ned.usgs.gov</a>
PSLC	2009	Lidar	~1 meter	NAD 83 WA State Plane North	NAVD 88	<a href="http://pugetsoundlidar.ess.washington.edu/">http://pugetsoundlidar.ess.washington.edu/</a>
CDED	2007	DEM	~8 meters	NAD 83 geographic	MSL	<a href="http://www.geobase.ca/data/cded/index.html">http://www.geobase.ca/data/cded/index.html</a>



*Figure 11. Source and coverage of topographic datasets used in compiling the San Juan Islands DEMs.*

### 1) United States Geological Survey National Elevation Dataset 1/3 arc-second topographic DEM

The USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the San Juan Islands region<sup>7</sup>. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD 88 vertical datum (meters). The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: <http://seamless.usgs.gov>). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys and topographic lidar. The NED DEM included “zero” elevation values over the open ocean, which were removed from the dataset by clipping to the “combined shoreline”.

NGDC used the NED 1/3 arc-second DEM in those regions where the NED 1/3 is derived from the higher resolution NED 1/9 data. In addition, the NED 1/3 was used where no NED 1/9, CDED, and lidar data exists (Fig. 11, 12).

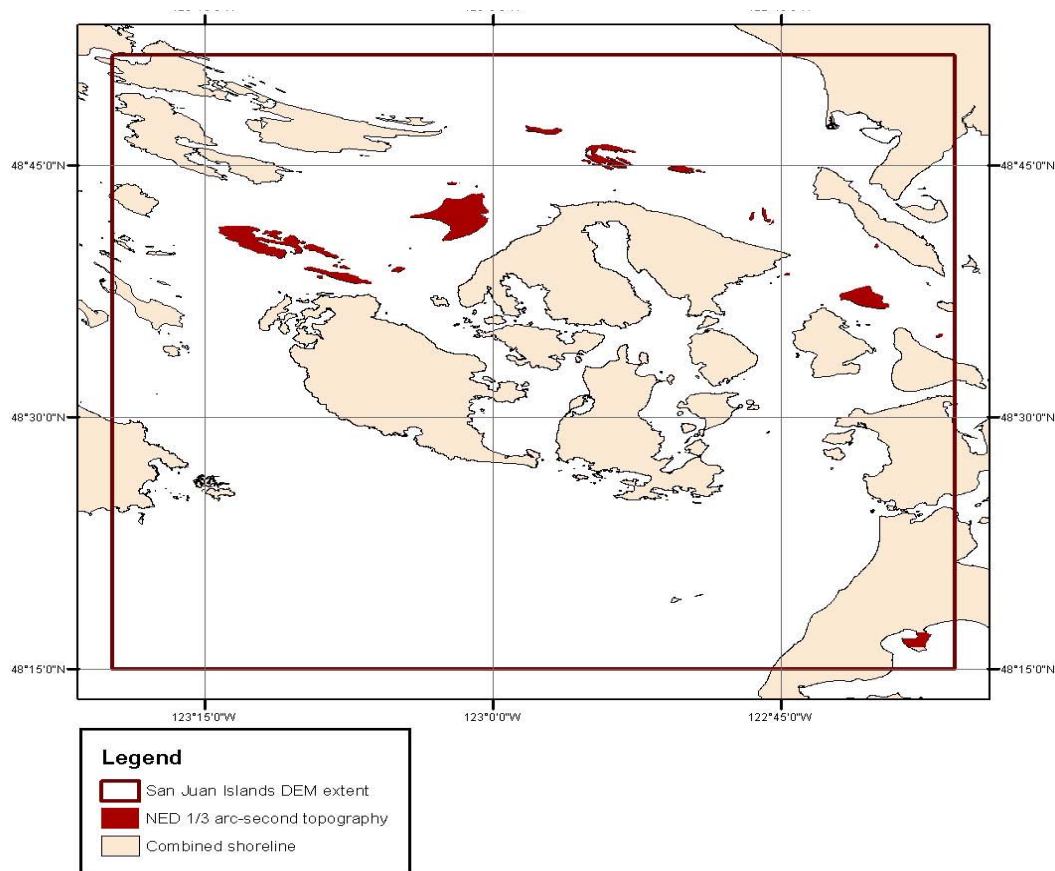


Figure 12. Coverage of the NED 1/3 arc-second topographic DEM used in building the San Juan Islands DEMs. This dataset was used only where higher resolution topography was unavailable.

7. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD 88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the “best available” DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]

## 2) United States Geological Survey National Elevation Dataset 1/9 arc-second topographic DEM

The USGS provides limited high-resolution NED 1/9 arc-second DEMs, derived from 3 meter point spacing lidar data. Data are in NAD 83 geographic coordinates and NAVD 88 vertical datum (meters), and are available for download as raster DEMs. The horizontal accuracy is 3 meters and the vertical accuracy, depending on the source data, is less than 22 centimeters. The NED 1/9 DEM included “zero” elevation values over the open ocean, which were removed by clipping to the “combined shoreline”.

In areas where recent lidar surveys have been conducted, the lidar superseded the older NED 1/9 arc-second DEM, primarily in the San Juan Islands (Fig. 11). In addition, the NED 1/9 contained sections of anomalous elevation values that were manually removed from the dataset (e.g., Fig. 13).

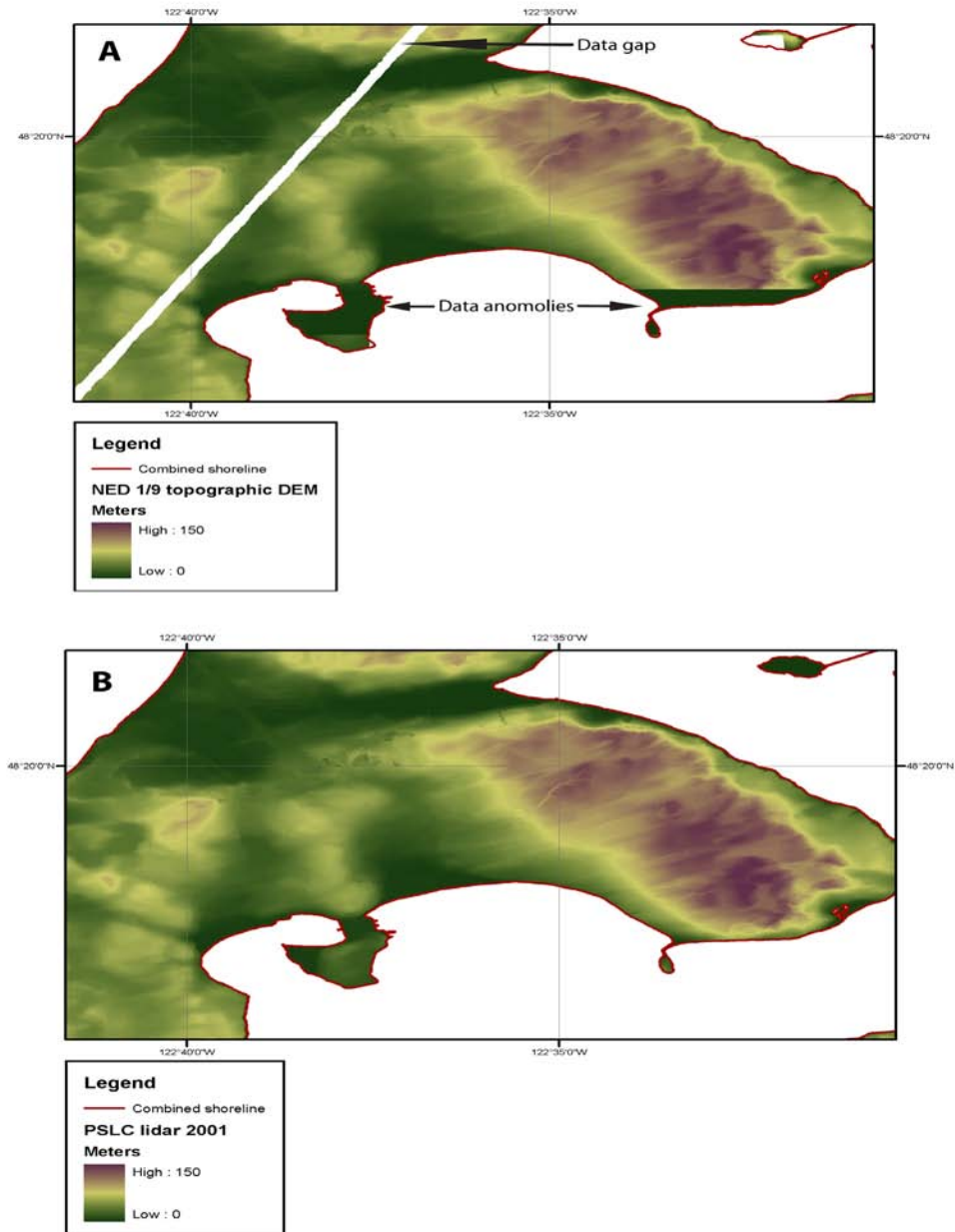


Figure 13. Comparison of the NED 1/9 arc-second data and the PSLC topographic lidar.

A. Data gaps and anomalies in the NED 1/9 arc-second DEM.

B. PSLC topographic lidar of the same region.

### 3) Puget Sound Lidar Consortium Lidar

PSLC is an informal group of local agency staff and federal research scientists devoted to developing public domain high-resolution lidar products for the Puget Sound region. Although PSLC provides extensive lidar coverage within the boundaries of the San Juan Islands DEM, the NED 1/9 arc-second topographic DEM integrates PSLC lidar collected prior to 2005. Lidar surveys conducted in 2009 of the San Juan Islands were used in the San Juan Islands DEM.

Although the NED 1/9 topographic DEM integrates PSLC lidar prior to 2005, it contained anomalous values and data gaps (e.g., Fig. 13). In these areas, PSLC lidar from 2001 and 2003 respectively, were used in the San Juan Islands DEM. Data are in NAD 83 Washington State Plane North projected coordinates and NAVD 88 vertical datum (meters), and have a vertical accuracy of ~1 meter.

### 4) Canadian Digital Elevation Dataset

CDED consists of an ordered array of ground elevations at regularly spaced intervals at scales of 1:50,000 and 1:250,000. For the region surrounding Vancouver Island, the grid spacing is 0.75 arc-seconds at the 1:50,000 scale (Fig. 14). Data are in NAD 83 geographic coordinates, referenced to MSL (meters), and are available for download as raster DEMs. The extracted elevations have a vertical accuracy of +/- 5 to 10 meters depending on the source data resolution. The data were clipped to the shoreline to remove values over the open ocean. See the CDED web site for specific source information (<http://www.geobase.ca/geobase/en/data/cded/index.html>).

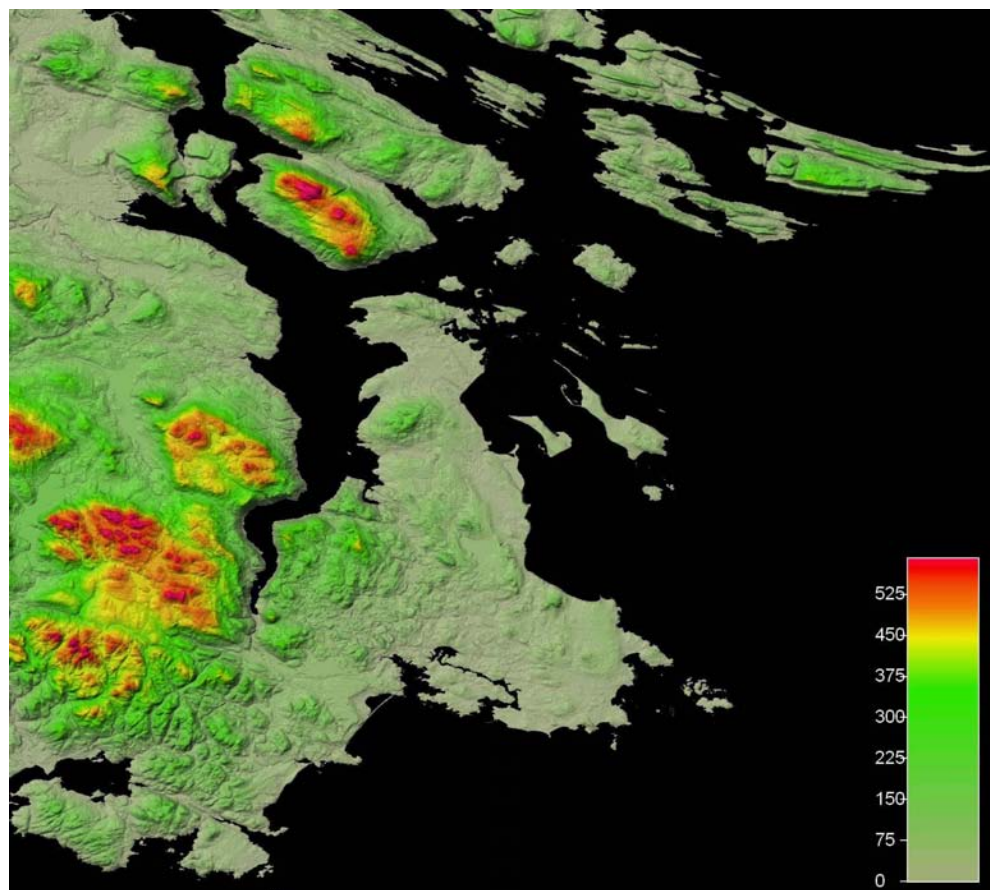


Figure 14. Color shaded-relief image of the CDED topographic DEM. Vertical units in meters.

## 3.2 Establishing Common Datums

### 3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the San Juan Islands NAVD 88 DEM were originally referenced to a number of vertical datums including MLLW, MLW, MSL, and NAVD 88. All datasets except for the Canadian topographic data were transformed to NAVD 88 using the *VDatum* transformation tool (<http://vdatum.noaa.gov/>). The tidal relationships at the Port Angeles tide stations (<http://tidesandcurrents.noaa.gov/>) are provided in Table 6. Locations of the tide stations are illustrated in Figure 22.

#### 1) Bathymetric data

The NOS hydrographic surveys, CHS bathymetric multibeam, and MLML bathymetric multibeam were transformed from MLW, MLLW, and MSL to NAVD 88 using *VDatum*.

#### 2) Topographic data

The NED 1/3 arc-second DEM, NED 1/9 arc-second DEM, and PSLC lidar were originally referenced to NAVD 88 and required no vertical transformation. The CDED DEM is a Canadian dataset originally referenced to MSL. NGDC used the relationship between MSL and NAVD 88 at the Port Angeles, WA tide station (Table 6). Conversion to NAVD 88, using *FME* software, was accomplished by subtracting a constant offset value of 1.166 meters.

Table 6. Relationship between NAVD 88 and other vertical datums at the Port Angeles tide station (# 9444090).

<i>Vertical datum</i>	<i>Value (m)</i>	<i>Difference to NAVD 88 (m)</i>
MHHW	2.153	2.024
MHW	1.987	1.858
MSL	1.295	1.166
MLW	0.586	.457
NAVD 88	0.129	0.00
MLLW	0.00	-0.129

### 3.2.2 Horizontal datum transformations

Datasets used to compile the San Juan Islands NAVD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 83 UTM Zone 10 North, NAD 83 Washington State Plane North, and WGS 84 Washington State Plane North. The relationships and transformational equations between the geographic horizontal datums are well established. After datasets were transformed to NAD 83 geographic, *MB-System* was used to convert and grid the San Juan Islands DEMs to a horizontal datum of NAD 83 HARN Washington State Plane South (ft) and a cell size of 1/3 arc-second.

### 3.3 Digital Elevation Model Development

#### 3.3.1 *Verifying consistency between datasets*

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in ESRI *ArcMap*, *Quick Terrain Modeler*, and *Fledermaus* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Inconsistent, overlapping topographic datasets. The lower resolution datasets were clipped to high resolution datasets.
- Data values over the ocean in the NED DEMs, CDED, and the PSLC lidar topographic datasets required automated clipping to the combined coastline or were edited manually.
- Digital, measured bathymetric values from NOS surveys date back over 123 years. More recent data, differed from older NOS data by as much as 50 meters vertically. The older NOS survey data were excised where more recent bathymetric data exists.

#### 3.3.2 *Processing of bathymetric data*

Older NOS hydrographic survey data are generally sparse at the resolution of the San Juan Islands DEMs in both deep water and in some areas close to shore. In order to reduce the effect of artifacts in the form of lines or “pimples” in the DEM due to these low resolution datasets, and to provide effective interpolation into the coastal zone, a 1/3 arc-second-cell size ‘pre-surface’ bathymetric grid in NAVD 88 vertical datum was generated using *GMT*<sup>9</sup>, an NSF-funded software application designed to manipulate data for mapping purposes (<http://gmt.soest.hawaii.edu/>).

The older NOS hydrographic point data, in xyz format, were clipped to remove overlap with the newer NOS surveys. All NOS hydrographic point data were clipped to remove overlap with the MLML and CHS bathymetric multibeam. All of the bathymetric data were combined with points extracted from the adjusted MHW coastline—to provide a buffer along the entire coastline.

The point data were then median-averaged using the *GMT* tool ‘blockmedian’ to create a 1/3 arc-second grid 0.05 degrees (~5%) larger than the San Juan Islands DEM region. The *GMT* tool ‘surface’ was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by ‘surface’ was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy. Figures 15 and 16 show histograms of the NOS and CHS multibeam compared to the 1/3 arc-second pre-surfaced bathymetric grid. Differences cluster around zero for all three datasets.

Some inconsistencies were identified while merging the bathymetric datasets due to the range in ages and resolutions of the NOS hydrographic surveys. In areas where more recent data were available, the older surveys were either edited or not used. The gridded bathymetric surface was then converted to an xyz file for use in building the NAVD 88 DEM.

---

9. GMT is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: <http://gmt.soest.hawaii.edu/> [Extracted from GMT web site.]

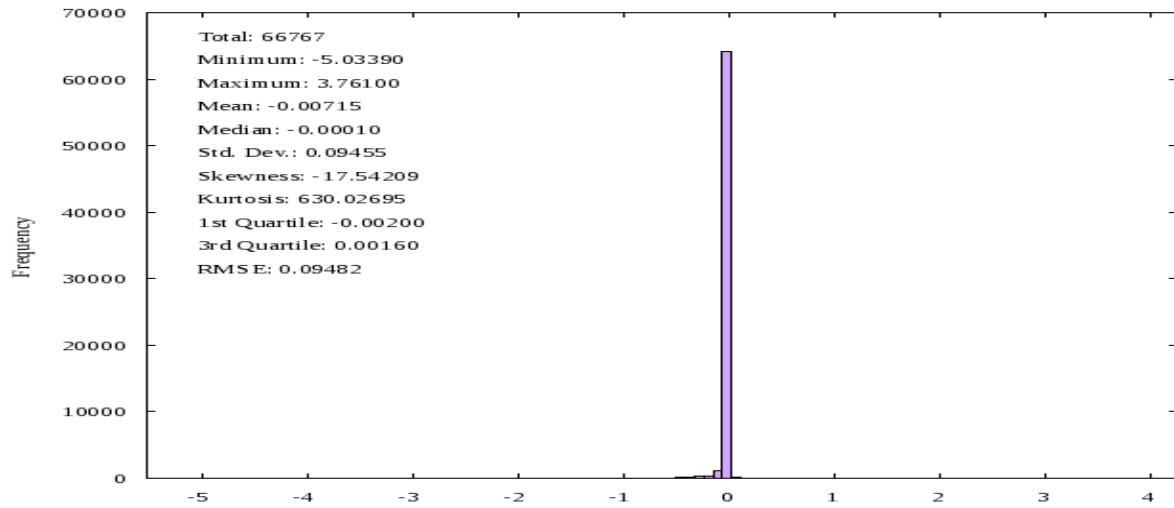


Figure 15. Histogram of the differences between NOS hydrographic survey H11316 and the 1/3 arc-second pre-surfaced bathymetric grid.

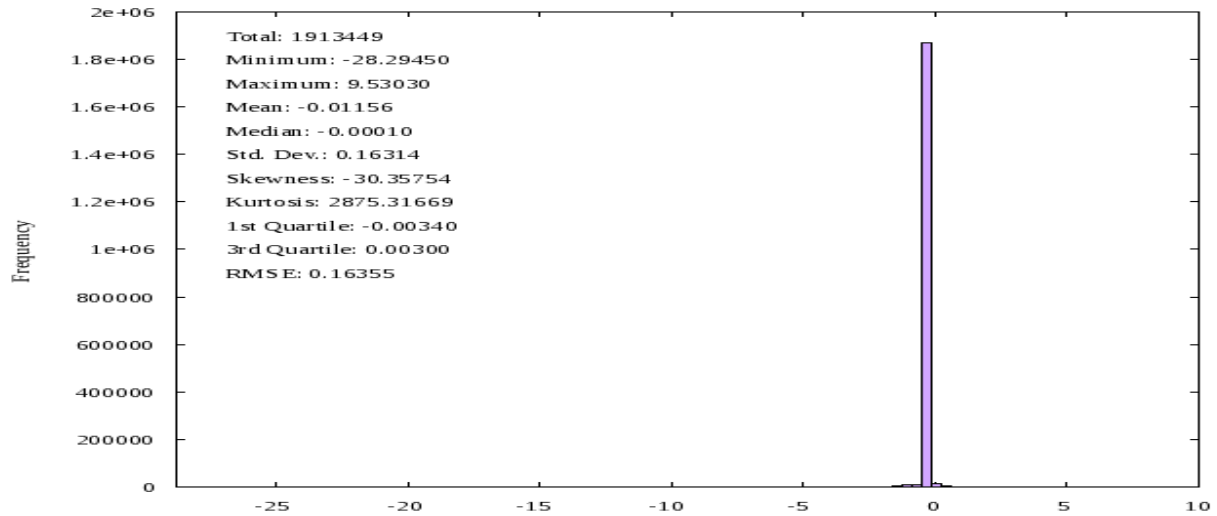


Figure 16. Histogram of the differences between the CHS multibeam swath sonar bathymetry and the 1/3 arc-second pre-surfaced bathymetric grid.

### 3.3.3 Building the NAVD 88 DEM

*MB-System* was used to create the 1/3 arc-second San Juan Islands NAVD 88 DEM. The *MB-System* tool ‘mbgrid’ was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the ‘mbgrid’ gridding algorithm, as relative gridding weights, is listed in Table 7. After datasets were transformed to NAD 83 geographic, *MB-System* was used to convert and grid the San Juan Islands DEMs to a horizontal datum of NAD 83 HARN Washington State Plane South (ft) and a cell size of 1/3 arc-second. Greatest weight was given to the NED 1/9 arc-second DEM, CHS multibeam, MLML multibeam, and PSLC topographic lidar. Least weight was given to the pre-surfaced bathymetric grid.

Table 7. Data hierarchy used to assign gridding weight in *MB-System*

<i>Dataset</i>	<i>Relative Gridding Weight</i>
USGS NED 1/9 Topographic DEM	100
PSLC topographic lidar	100
CHS Multibeam	100
MLML Multibeam	100
NOS hydrographic surveys	10
USGS NED 1/3 Topographic DEM	10
CDED topographic DEM	10
NGDC digitized elevations	1
NGDC Bathymetric Surface	0.01

### 3.3.4 Building the MHW DEM

The MHW DEM was created by adding an NAVD 88-to-MHW conversion grid to the NAVD 88 DEM.

#### 1) Developing the conversion grid

Using extents slightly larger (~ 5 percent) than the DEM, an initial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* tool ‘surface’ applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-value grid was then converted to an intermediate xyz file using the *GMT* tool ‘grd2xyz’.

Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum*. Null values were removed and a converted xyz file was created by clipping the data to the combined shoreline using *FME*. The converted xyz file was then interpolated with the *GMT* tool ‘surface’ to create the 1/3 arc-second ‘NAVD 88 to MHW’ conversion grid with the extents slightly larger (~ 5 percent) than the NAVD 88 DEM (Fig. 17).

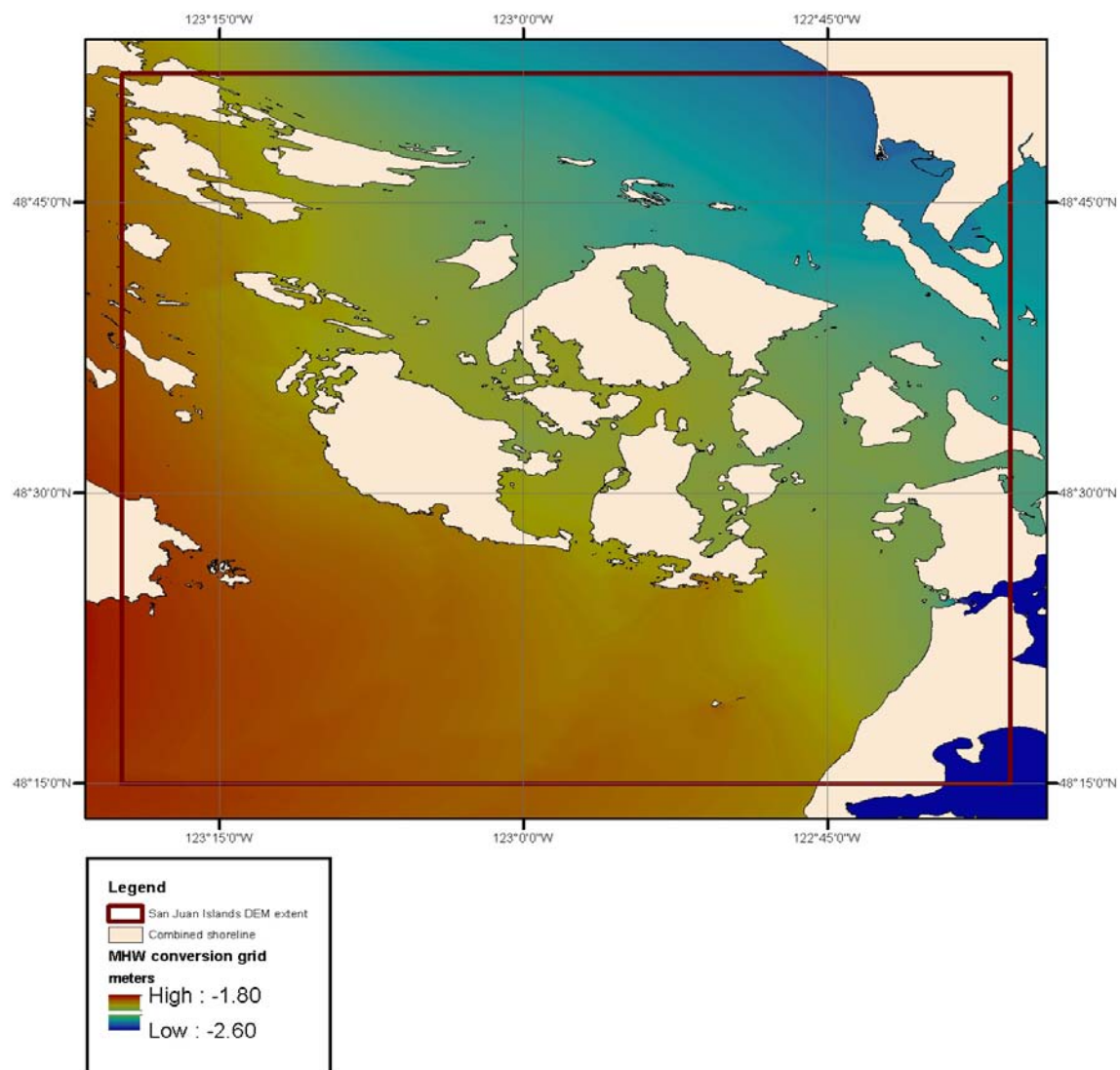


Figure 17. Image of the NAVD 88 to MHW conversion grid used to generate the MHW DEM.

## 2) Assessing the accuracy of the conversion grid

The NAVD 88-to-MHW conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLLW to NAVD 88 using *VDatum*. Shapefiles of the resultant xyz files were created and null values removed using *FME*. The shapefiles were then merged to create a single shapefile of all NOS surveys with a vertical datum of NAVD 88. A second shapefile of NOS data were created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 shapefiles were computed after performing a spatial join in *ArcGIS*.

To verify the conversion grid methodology, the difference shapefile created using *ArcGIS* was converted to xyz format using *FME*. The 'NAVD 88-to-MHW' grid was then compared to the difference xyz file. Figure 18 indicates an agreement to approximately +/- 0.00640 meters with a mean difference of 0.00008 meters. Errors in the source datasets require rebuilding only the NAVD 88 DEM.

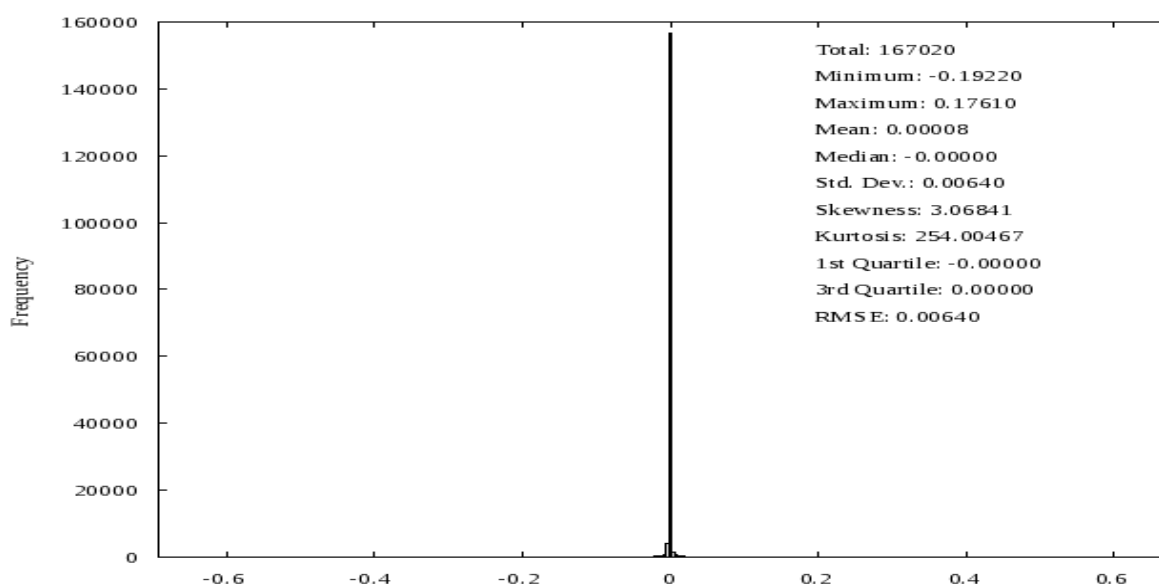


Figure 18. Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.

## 3) Creating the MHW DEM

Once the NAVD 88 DEM was complete and assessed for errors, the NAVD 88 to MHW conversion grid was added to it using *ArcCatalog*. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery. Problems encountered were determined to reside in source datasets, and were corrected before building a new NAVD 88 DEM.

### 3.4 Quality Assessment of the DEMs

#### 3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the San Juan Islands DEMs are dependent upon DEM cell size and source datasets. Topographic features in the DEMs have an estimated horizontal accuracy of 10 meters: gridded PSLC lidar data have an accuracy of approximately 1 meter, NED 1/3 topographic DEM is accurate to approximately 10 meters, NED 1/9 topographic DEM is accurate to approximately 3 meters, and the CDED topographic DEM is accurate to approximately 8 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings and potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

#### 3.4.2 Vertical accuracy

Vertical accuracy of elevation values in the San Juan Islands DEMs are dependent upon the source datasets contributing to DEM cell values. Topographic data have an estimated vertical accuracy of approximately 0.1 meters for PSLC lidar data, approximately 1 meter for the NED 1/9 arc-second DEM, and 7-15 meters for the NED 1/3 arc-second DEM. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. Those values were derived from the wide range of sounding measurements from the early 20<sup>th</sup> century to recent, GPS-navigated multibeam swath sonar survey. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

#### 3.4.3 Slope map and color shaded-relief map

ESRI *ArcCatalog* was used to generate a slope grid from the San Juan Islands NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 19). The NAVD 88 DEM was transformed to NAD 83 UTM Zone 10 North coordinates in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Analysis of preliminary grids using *QT Modeler* and *Fledermaus* revealed suspect data points, which were corrected before recompiling the DEM. Figures 20 and 21 show a color shaded-relief image and a data contribution plot of the San Juan Islands NAVD 88 DEM, respectively.

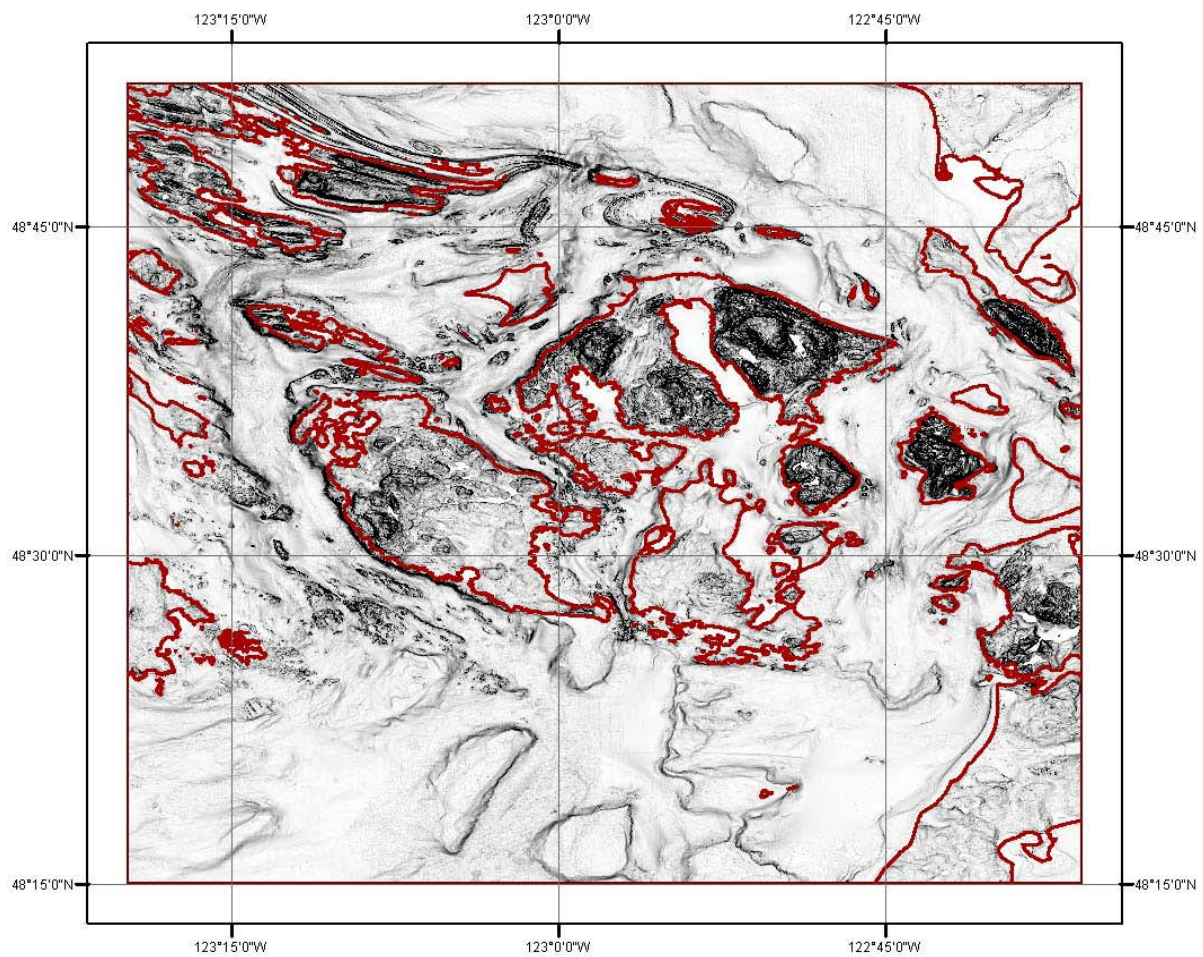
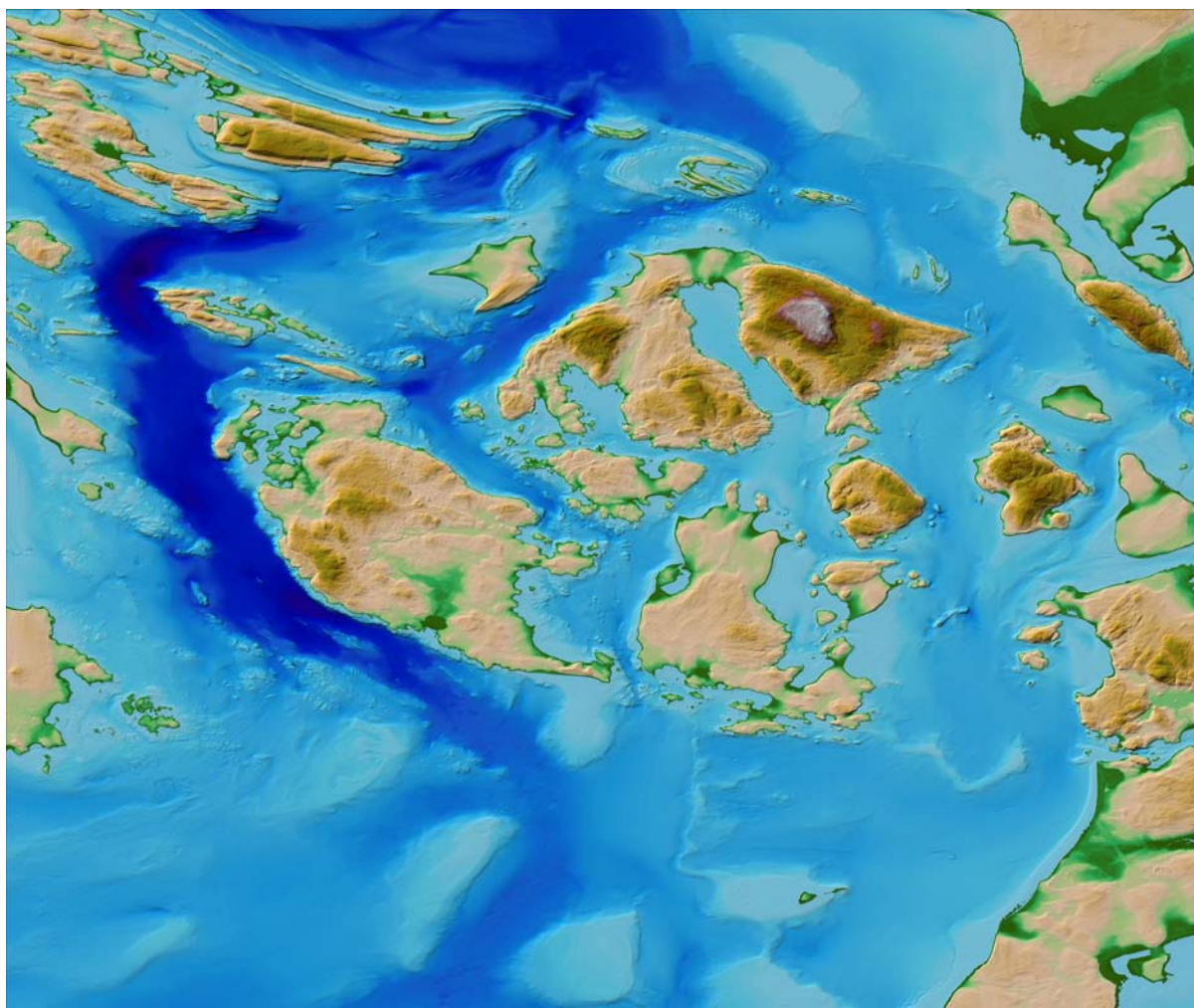


Figure 19. Slope map of the San Juan Islands NAVD 88 DEM. Flat-lying slopes are shown in white; dark shading denotes steep slopes; combined shoreline indicated in red.



*Figure 20. Color-shaded relief image of the NAVD 88 San Juan Islands DEM.*

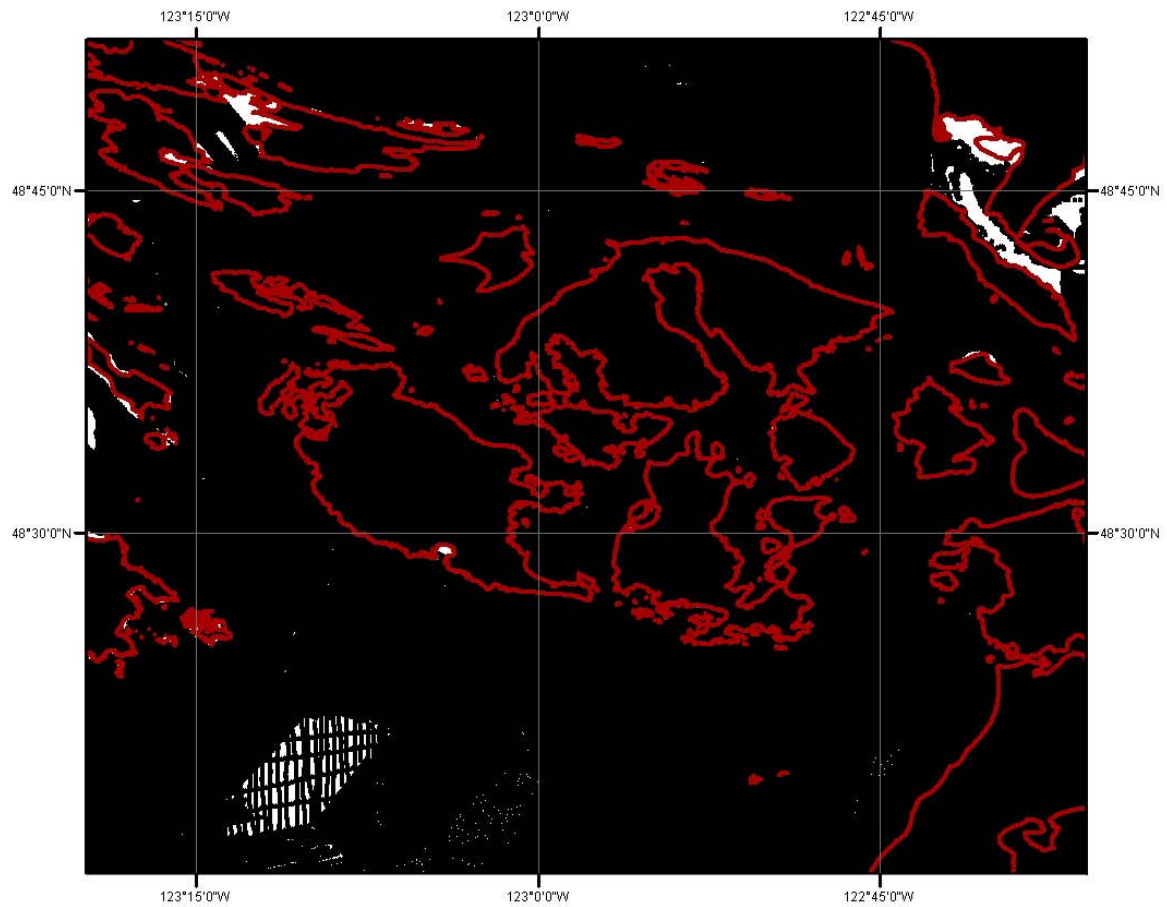


Figure 21. Data contribution plot of the San Juan Islands DEMs. Black depicts DEM cells constrained by source data; white depicts cells with elevation values derived from interpolation. Due to the scale of the image, sparse soundings may not be visible in the graphic. Shoreline is shown in red.

### 3.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 730 U.S. geodetic monuments were extracted from the NOAA NGS web site (<http://www.ngs.noaa.gov/>) in shapefile format (see Fig. 22 for monument locations). Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Elevations were compared to the San Juan Islands NAVD 88 DEM (Fig. 23). Differences between the DEM and the monument elevations range from -27.40 to 345.48 meters. The majority are within several meters. Large differences in elevations occurred where monuments are located on road cuts, on the top of buildings, or have conversion errors evident on the NGS data sheet (e.g., feet instead of meters).

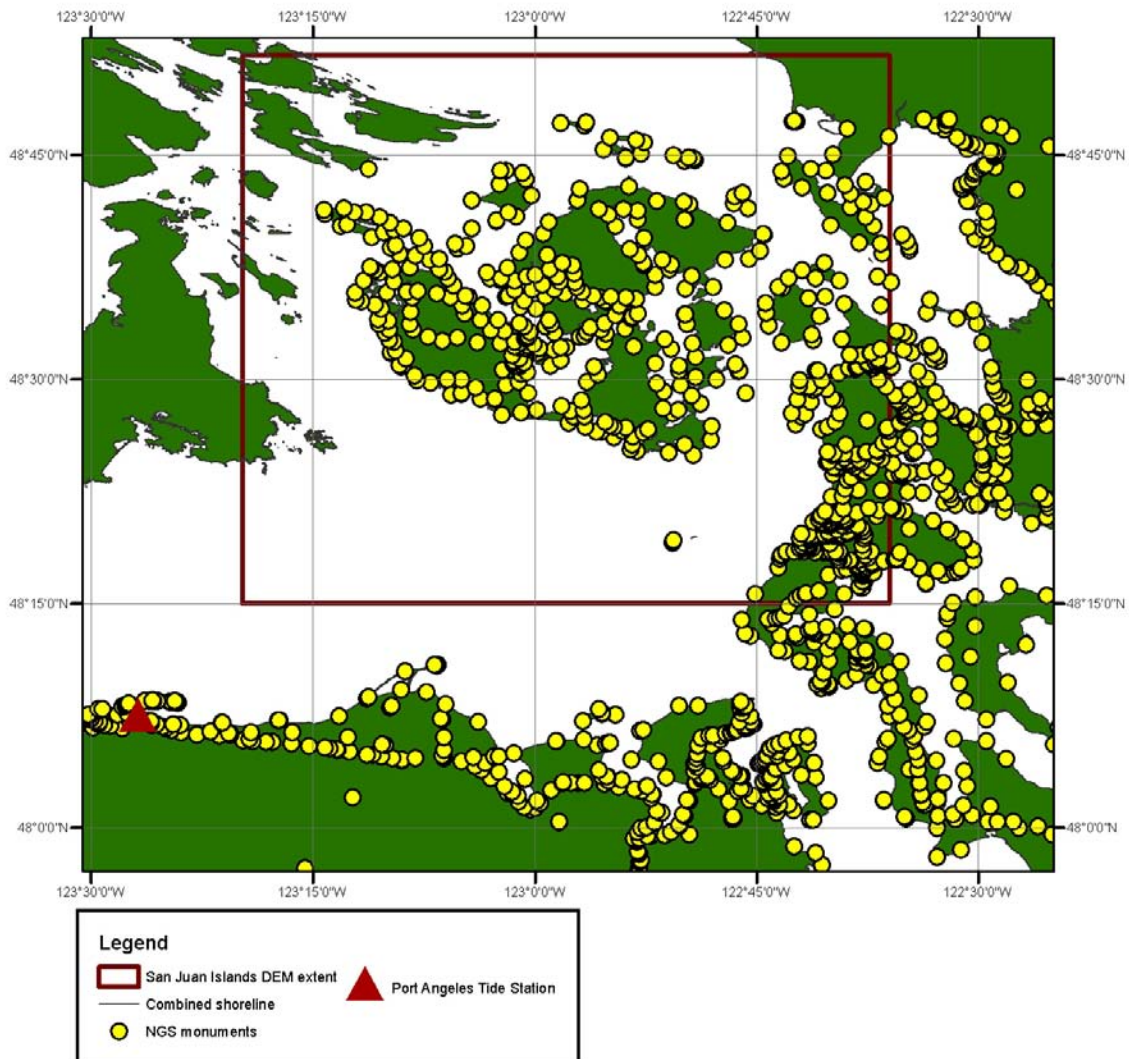


Figure 22. Location of NGS geodetic monuments, shown as yellow circles, in the San Juan Islands region. The Port Angeles tide station, shown as a black triangle.

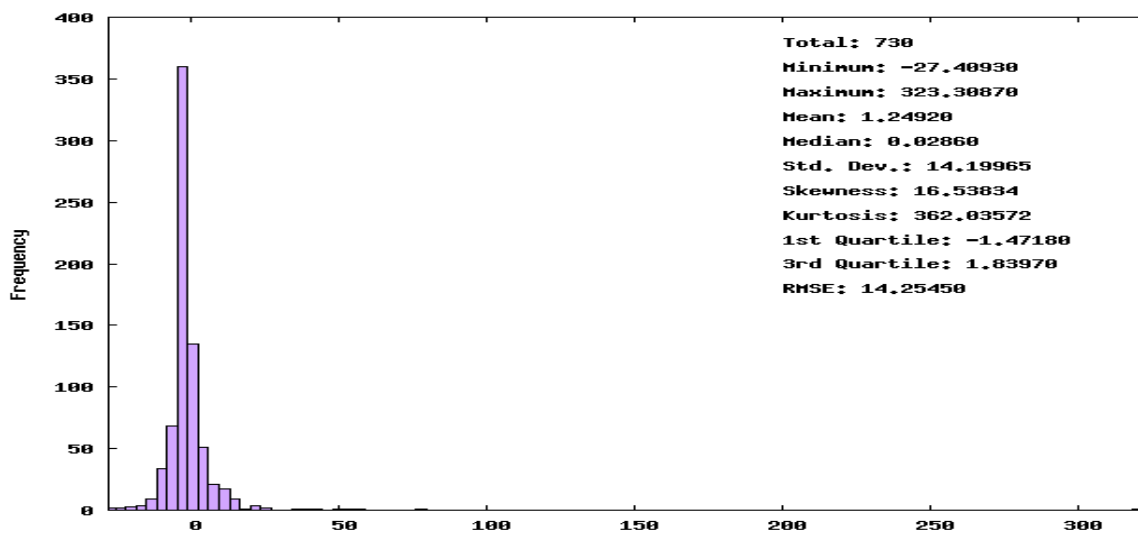


Figure 23. Histogram of the differences between NGS geodetic monument elevations and the San Juan Islands NAVD 88 DEM.

### 3.4.5 NAVD 88 DEM comparison with source data files

To ensure grid accuracy, select bathymetric and topographic source data files were compared to the San Juan Islands NAVD 88 DEM using *Fledermaus*, *FME* and *ArcMap*.

A histogram of the differences between data points from the PSLC topographic lidar data DEM and the San Juan Islands NAVD 88 DEM is shown in Figure 24. Differences cluster around zero with the majority are within  $\pm 0.5$  meters.

A random selection of NED 1/9 topographic points were compared to the San Juan Islands NAVD 88 DEM (Fig. 25; a random selection was used to represent the overall survey as there were too many points to statistically compare with current processing methods). The histogram shows the differences in elevations are clustered around zero and the majority are within  $\pm 1$  meter.

Comparison of all the CDED topographic points and the San Juan Islands NAVD 88 DEM are shown in Figure 26. The histogram shows the differences in elevations are clustered around zero with the elevation differences ranging from -0.0064 to +25.27. The largest differences occur along the edge of steep slopes.

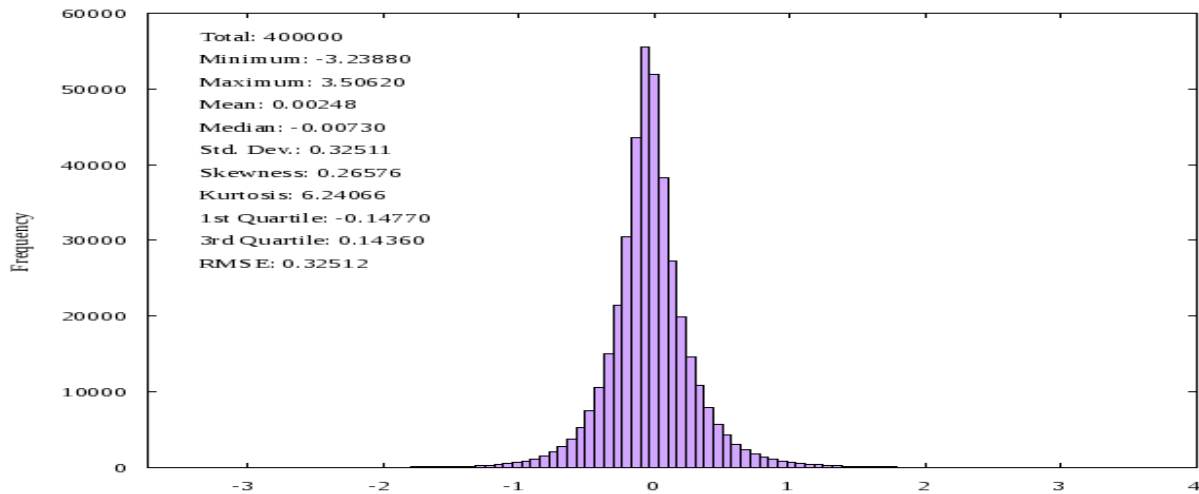


Figure 24. Histogram of the differences between select PSLC topographic data points and the San Juan Islands NAVD 88 DEM.

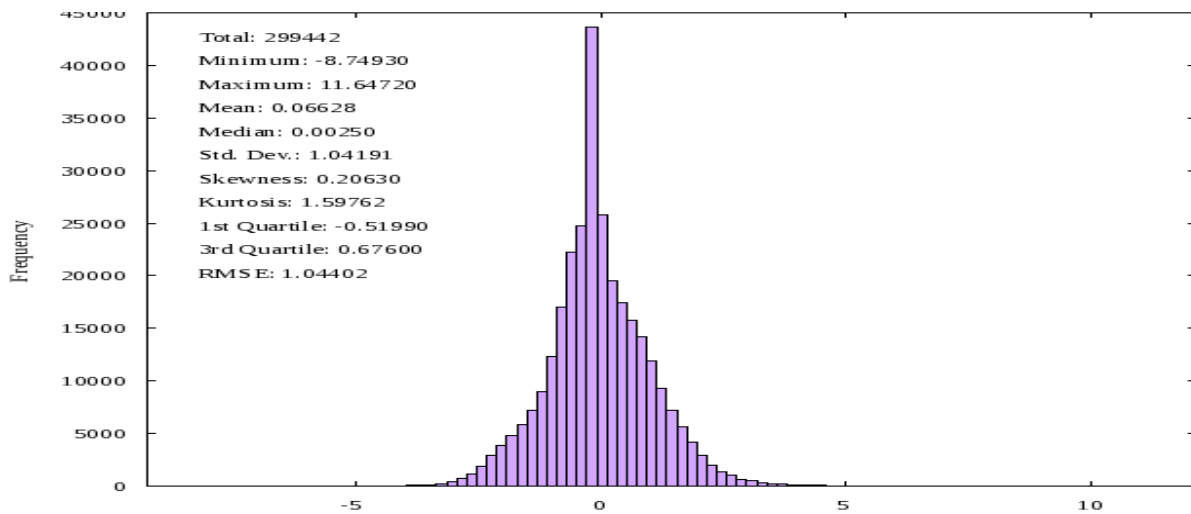


Figure 25. Histogram of the differences between select NED 1/9 data points and the San Juan Islands NAVD 88 DEM.

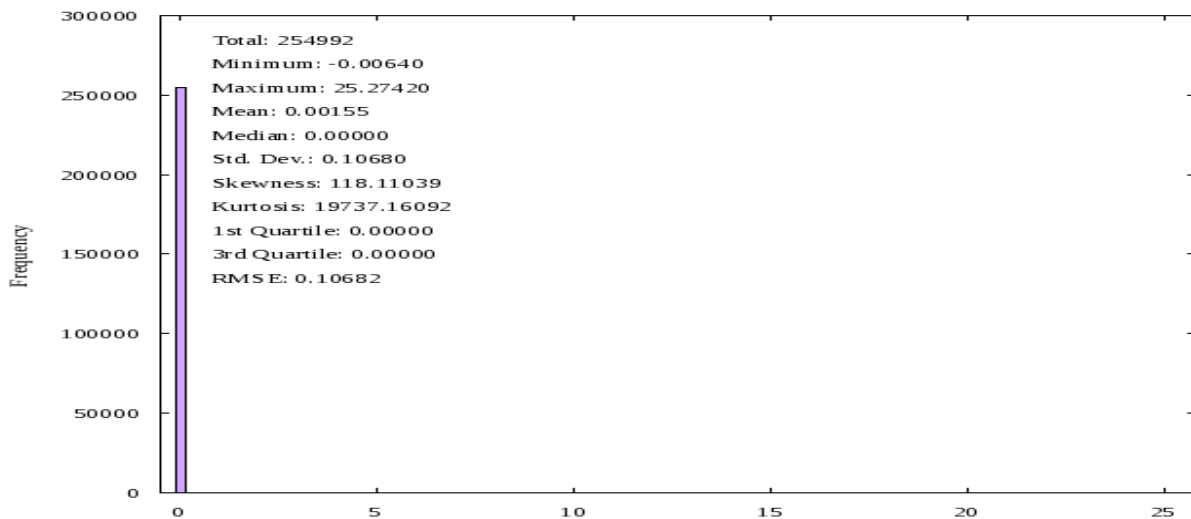


Figure 26. Histogram of the differences between CDED topographic data points and the San Juan Islands NAVD 88 DEM.

#### 4. SUMMARY AND CONCLUSIONS

Two integrated bathymetric–topographic digital elevation models of the San Juan Islands, Washington region were developed for the National Tsunami Hazard Mitigation Program (NTHMP). The best available digital data from U.S. federal, international, state, local, and academic agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before generating the DEM. The data were quality checked, processed and gridded using ESRI *ArcGIS*, ESRI *ArcGIS World Imagery 2-D*, *FME*, *Fledermaus*, *GMT*, *GDAL*, *MB-System*, *QT Modeler*, and *VDatum* software.

Recommendations to improve the San Juan Islands DEMs, based on NGDC’s research and analysis, are listed below:

- Conduct high-resolution bathymetric surveys in Plumper Sound.
- Conduct bathymetric-topographic lidar surveys in lowland areas along estuaries.
- Extend VDatum coverage into Canada.

#### 5. ACKNOWLEDGMENTS

The creation of the San Juan Islands DEMs were funded by the National Tsunami Hazard Mitigation Program (NTHMP). Special thanks to Rob Hare (CHS) and Gary Greene (MLML) who provided Canadian multibeam bathymetry and Moss Landing multibeam bathymetry, respectively.

#### 6. REFERENCES

Nautical Chart #18400, 48th Edition, 2008. Strait of Georgia and Strait of Juan De Fuca. Scale 1:200,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18421, 49th Edition, 2008. Strait of Georgia and Strait of Juan De Fuca. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #18440, 30th Edition, 2010. Plumper Sound. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

#### 7. DATA PROCESSING SOFTWARE

ArcGIS v. 10.0 – developed and licensed by ESRI, Redlands, Washington, <http://www.esri.com/H>

ESRI World Imagery (ESRI\_Imagery\_World\_2D) – ESRI ArcGIS Resource Centers <http://resources.esri.com/arcgisonline/services/>.

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, <http://www.safe.com/>.

Fledermaus v. 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, <http://www.ivs3d.com/products/fledermaus/>.

GDAL v. 1.7.1 – Geospatial Data Abstraction Library, Open Source Geospatial Foundation, <http://www.gdal.org>

GEODAS v. 5 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, <http://www.ngdc.noaa.gov/mgg/geodas/>.

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, <http://gmt.soest.hawaii.edu/>

MB-System v. 5.1.0 – software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, <http://www.ldeo.columbia.edu/res/pi/MB-System/>.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University’s Applied Physics

Laboratory (APL) and maintained and licensed by Applied Imagery, <http://www.appliedimagery.com/>  
VDatum Transformation Tool, Washington - Washington Juan De Fuca, v. 01 – developed and maintained by NOAA's  
National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic  
Products and Services (CO-OPS), <http://vdatum.noaa.gov/>.

VDatum Transformation Tool, Washington - Washington Puget Sound, v. 01 – developed and maintained by NOAA's  
National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic  
Products and Services (CO-OPS), <http://vdatum.noaa.gov/>.

